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VOLUME 53 NUMBER 6

BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA

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DECEMBER, 1963

SPECIAL ISSUE—OCEANOGRAPHIC, GEOLOGIC, AND ENGINEERING STUDIES OF THE CHILEAN EARTHQUAKES OF MAY 1960

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SEISMOLOGICAL SOCIETY OF AMERICA

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ITS OBJECT

I. To promote research in seismology, the scientific investigation of earthquakes and related phenomena.

II. To promote public safety by all practical means.

III. To enlist the interest of engineers, architects, contractors, insurance men, and property owners in the obligation to protect the community against disasters due to earthquakes and earthquake fires by showing that it is reasonably practicable and economical to build for security.

IV. To inform the public by appropriate publications, lectures, and other means to an understanding of the fact that earthquakes are dangerous chiefly because we do not take adequate precautions against their effects, whereas it is possible to insure ourselves against damage by proper studies of their geographic distribution, historical sequence, activities, and effects on buildings.

BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA

A subscription to the Bulletin is included in membership dues. The subscription rate for non-members is $12 a year. Forms for membership application and for subscriptions are included near the back of this *Bulletin.*

The *Bulletin of the Seismological Society of America* was first issued in 1911 and was a quarterly publication through 1962: It is now issued six times a year. Most back numbers of the *Bulletin* are still available from the Secretary, and are, in general, sold at $3 a copy. Exceptions are: Vol. 29, No. 1: $6.00 (Descriptive Catalogue of Earthquakes of the Pacific Coast of the United States, 1769 to 1928); and Vol. 44. No. 2B: $7.00 (An Engineering Study of the Southern California Earthquake of July 21, 1952, and Its After-shocks).

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Manuscripts offered for publication should be submitted to the Editor (see back cover for current address). A brief abstract must accompany each manuscript. Reprints, if desired by authors, must be ordered at the time corrected page proofs are returned to the Editor.

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The papers in this number were edited by Pierre Saint-Amand for the Earthquake Engineering Research Institute prior to submission to the Society.

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Bulletin of the

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PREFACE

By Pierre Saint-Amand

When the earthquakes of May 1960 desolated south-central Chile, the scientific forces of that country were mobilized to study the effects of the earthquakes and to advise the Chilean government of whatever steps needed to be taken for immediate relief and for subsequent reconstruction. Many others proceeded on their own initiative to make investigations. The results of these efforts were sometimes published, more often simply prepared as mimeographed reports.

It was with a view to preserving this information that my colleagues and I have translated the reports contained herein from the several languages in which they appeared. We have not included material available in the same form in publications in some readily accessible journal.

Some of the papers came to us in English and required only the most minor emendations. The papers on the tsunamis in the Pacific were in this category. The paper by Wright and Mella on geomorphic effects will probably become a classic in its field since, in addition to being very well done, it is the first to my knowledge to cover the sort of effects it describes—this paper was also submitted in English.

Some of the papers in Spanish were prepared with great care and with a fine literary style. These have perhaps suffered from my heavy-handed translation—for this I apologize. A paper in this category is the report prepared by the Chilean Navy on the effects of the "maremoto" on the Chilean coast. This is probably the most complete work ever assembled on the effects of a tsunami in an epicentral area. It represents a fine compilation and sifting of data from many sources. The graphic style and salty phraseology lend a dramatic touch to the excellent account.

Some of the papers prepared in Spanish were, of course, written hurriedly in answer to an urgent need for the information. For most of the authors this had been their first earthquake investigation and hence the papers show a certain divergence from what would have been reported by an experienced seismologist. In some ways this has been good because although many of these papers contain more geology than seismology the effects of the earthquakes were so clearly dependent on the geology that the information is needed to in order to properly understand the engineering aspects of the earthquakes. Indeed, most of the papers in Spanish were written specifically for purposes of guiding reconstruction.

The translators tried to retain the original phraseology as best they could; however, many papers were somewhat redundant and contained non-pertinent information. Having appointed myself an editor, I felt a certain need to shorten or to extend and clarify some of these papers. Many new figures were introduced. Whenever possible, translations were submitted to at least one of the authors; if the author had left Chile, the ones remaining in Chile were called upon to check the manuscripts. In many cases new data were available and were incorporated, and the meaning of certain terms peculiar to Chile were clarified. Because of the distances and time involved, some of the changes were made without the knowledge of the author. For this I pray their indulgence.

A few controversial points arose and when these were matters of observation they were left unchanged. When matters of interpretation, they were usually accepted even when verging upon idle speculation. In many cases conclusions quite opposite to mine were included. For example, Weichet shows two centers of intensity for the main earthquake. The center in the lake region near Purrangue is due in my opinion to an aftershock or aftershocks occurring on a quite different fault from the main shock.

Another divergence of opinion arises over the papers on Valdivia where it is quite clear that the several authors have arrived at opinions that differ not only over the sinking of the coast, but over the mode of destruction in the town. Here it is quite clear that a combination of effects offers the answer.

The paper on the volcanoes of Chile offers a good bit of historical and taxonomic information and was to accompany a more general discussion of the geology. Unfortunately, I was unable to finish it in time for this publication. The reader is referred to my papers in the bibliography for a very sketchy summary of the geology. Similarly a longer general discussion by myself has had to be left out and again reference to my earlier papers will fill this gap.

A complete intensity map was to have been prepared by the Institute of Geophysics of the University of Chile; unfortunately the several thousand intensity questionnaire cards filled out by the field workers were lost in a fire.

Several papers on the psychological and civil affairs aspects were studied and translated but not used, primarily because a line had to be drawn somewhere in limiting the aspects to be covered. These works are available in Spanish from the University of Chile. A discussion of these matters is indeed useful and hence attempts will be made to enlarge upon this theme elsewhere.

This collection has been helped and encouraged and indeed is a contribution of the Earthquake Engineering Research Institute. Publication has been supported by a grant from the National Science Foundation. Information collection was supported by the Escuela de Geologia and the Instituto de Geologia of the University of Chile, the Instituto de Investigacciones Geologicas, the Chilean Air Force, Chilean Navy, Corporation de Fomento. The field work of myself and most of the other North Americans involved was supported by the International Cooperation Administration, predecessor of AID, through the United States Geologic Survey. The United Nations supported Dr. Wright and Sr. Mella.

The U. S. Air Force furnished transportation as did the U. S. Navy, U. S. Army and private individuals.

The U. S. Naval Ordnance Test Station, China Lake, California, supported a large part of the office work, editorial and secretarial help, drafting facilities, etc. To all of these people I am personally very grateful.

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THE SEISMIC SEA WAVE OF 22 MAY 1960 ALONG THE CHILEAN COAST

By Hellmuth A. Sievers C. (Parts I–III), Guillermo Villegas C. (Part IV), and Guillermo Barros (Preface)
(Translated by Pierre Saint-Amand)

PREFACE

Immediately following the earthquake and the tsunami that struck Southern Chile and inflicted extensive damage in ten provinces, parties of scientists (principally geologists) began to investigate the causes, the damage, and the possibilities of preventing or ameliorating the effects of future seismic movements. Scientists and engineers arrived from Japan, Mexico, North America, France, and other countries and, with the Chileans, began to study the situation in the hope of encountering some means by which earthquakes can be predicted and of developing techniques for preventing the great destruction caused by these phenomena.

The Chilean Navy put in movement practically all of its boats to help the villages that were affected, to make hydrographic studies that would permit navigation in the wide zone affected, and to give security to the ships of war and merchant vessels cooperating with them. Principally this work was done in the mouths of rivers, in rivers, in bays, in canals, and in all those places that might have suffered changes as a result of the earthquake.

The Oceanographic Section of the Navy's Department of Navigation and Hydrography was put into action to collect the maximum amount of information possible concerning the seismic sea wave; the maritime authorities helped with this study in each place. They succeeded in collecting information that has permitted a general study of the phenomena.

The number of tidal-wave victims has not been determined, and very probably the number of lives lost never will be known. Nor is there sufficient information to determine the locations of the epicenters nor to formulate any theories concerning the formation of the maremotos (seismic sea waves).

With the object of maintaining a predetermined order in the description of the phenomena, the material is arranged geographically, beginning in Aysen (the southernmost point at which effects were felt and from which data was obtained) and going north. (Punta Arenas and its immediate zones were not affected, as can be seen from examination of the tidegram from that place.)

All the times mentioned here are official Chilean time, International Zone Plus Four, except when expressly indicated. In general, the data have been compiled by people who have not had a scientific education, but who have done all possible to give complete and accurate information.

Part I. General Description

At 0604 hours on 21 May, a great earthquake with its epicenter in the zone of Concepción caused extensive damage to the towns in that area. As any earthquake that occurs near the coast may give rise to a maremoto, there existed the possibility that one may have been produced. In fact, the tidal record at Valparaíso registered a small alteration beginning at about 0900, consisting of waves 20 to 30 cm in height with a period of 20 to 25 minutes (figure 1 cc to 1 ii: all tidal records are in pocket at rear of this number). This abnormal activity continued all during the day and part of the night but decreased gradually.

The Department of Navigation and Hydrography, in compliance with its obligation as a member of the alarm system for Pacific tidal waves, contacted the central headquarters of this system in Honolulu, keeping them constantly informed. The earthquake also had registered on the seismographs of the Magnetic Observatory of Honolulu, and the Observatory had sent immediate inquiries to those recording stations around the Pacific who they thought might have registered abnormal waves. The state of alert began in the central stations of the alarm system in Hawaii at 0645 hours and terminated at 2049 hours, at which time it was demonstrated that the earthquake of Concepción had not given origin to a tidal wave. During the state of alert, cables were sent to various points in the Pacific from the central office inquiring about abnormalities.

All the tidal meters in Chile from Valparaíso to the north registered small abnormalities with the same characteristics as those at Talcahuano, but this, in general, went almost unnoticed, and their passage neither damaged nor interrupted maritime operations. As a precaution, a permanent watch was maintained at the tidal station of Valparaíso to verify any possible further abnormalities.

At approximately 1510 hours on 22 May, there was another earthquake of great proportions, with an epicenter apparently in the province of Llanquihue, that caused grave damage in the provinces between Concepción and Chiloé. The cities most affected were Puerto Montt, Valdivia, Ancud, Castro, and Corral. This earthquake originated a maremoto of such proportions that it destroyed all of the ports of this zone, producing tremendous damage. The first information received was from Lebu and referred to waves between 3 and 4 meters in height that were damaging the port. Shortly thereafter, notices began to arrive, confused by the difficulty of communication, that referred to successive marine waves that were causing devastation in Ancud, Bahía Mansa, Corral, Puerto Saavedra, etc. Upon receiving this information at 1630 hours, the Department of Navigation and Hydrography sent a cable to Honolulu, giving them the information needed to put the entire system into a state of alert. A short time afterwards, new cables were sent with more concrete information. The tide gage in Valparaíso began to register the first waves at 1613 hours, when the water rose rapidly some 74 cm in 16 minutes, lowering again rapidly a short time later. The successive rising and falling movements continued, as shown in figures 1 cc 1 ii.

The alarms of the seismographs sounded at 1538 hours in the Magnetic Observatory of Honolulu. Five minutes before the arrival of the cable from Valparaíso, the observatory sent the following bulletin:

"This bulletin is a tidal wave alert. A violent earthquake has occurred in Chile, the third in that area in the last 36 hours. It is possible that it has generated a large tsunami. Although we have as yet no data, we are awaiting information from Valparaíso and from Balboa. If a tidal wave has been originated it should arrive about midnight Hawaiian time today at the Island of Hawaii and 30 minutes later at the Island of Oahu. New information will be given as soon as more data is available."

Later, new bulletins were sent with information received from Valparaíso and from the various islands that were being affected by the tsunami. The picture was being completed at 0047 hours, 9 hours after the earthquake, and the following message was sent from Hawaii:

"This is a tidal wave alert bulletin. A violent earthquake in Chile has caused a tidal wave that is radiating in all directions over the Pacific Ocean. It is estimated that the first wave will reach the Island of Hawaii at midnight Hawaiian time and 30 minutes later at the Island of Oahu. Its destructive effects will last several hours. The intensity of the wave cannot be predicted. The southern part of Hawaii will be the first to be affected and will be the first indication of the damage that might be produced in other parts and other islands of the Hawaiian group. The times have been calculated for the arrival at other Pacific islands based on the best data obtainable; they are not very exact: Tahiti 0230 hours, Christmas Island 0400 hours, Samoa 0500 hours, Fiji and Canton 0600 hours, Johnston 0700 hours, and Midway 0830 hours."

The interchange of communications continued constantly, and data of the arrival of the tidal wave were received in the following manner: At 0330, a cable was dispatched from Tahiti advising of the arrival of the first wave; at 0430, Samoa informed of the arrival of the first wave; at 0458, Christmas Island informed of the arrival of the first wave; etc.

The messages arrived one after another, informing of the advances of the tidal waves. At 0654, the first wave arrived at the Hawaiian Islands, producing great damage in Hilo; but the activity of the Magnetic Observatory at Honolulu did not cease. At 1211 on 23 May, the state of alarm on the Hawaiian Islands terminated, but the waves of the tsunami continued their destructive voyage until they were stopped and then reflected by the coasts of Japan, Russia, New Zealand, Australia, etc.

PART II. DESCRIPTION BY PORTS BETWEEN AYSEN AND LOTA, INCLUDING THE ISLANDS JUAN FERNANDEZ AND PASCUA

Aysen: One might think that the effects of the tsunami might not have been noticed in Aysen, its river, and the nearby ports of Chacabuco, Aguirre, and Melinka, because they are located in a network of canals (figure 2). Nevertheless, three waves were felt in these places.

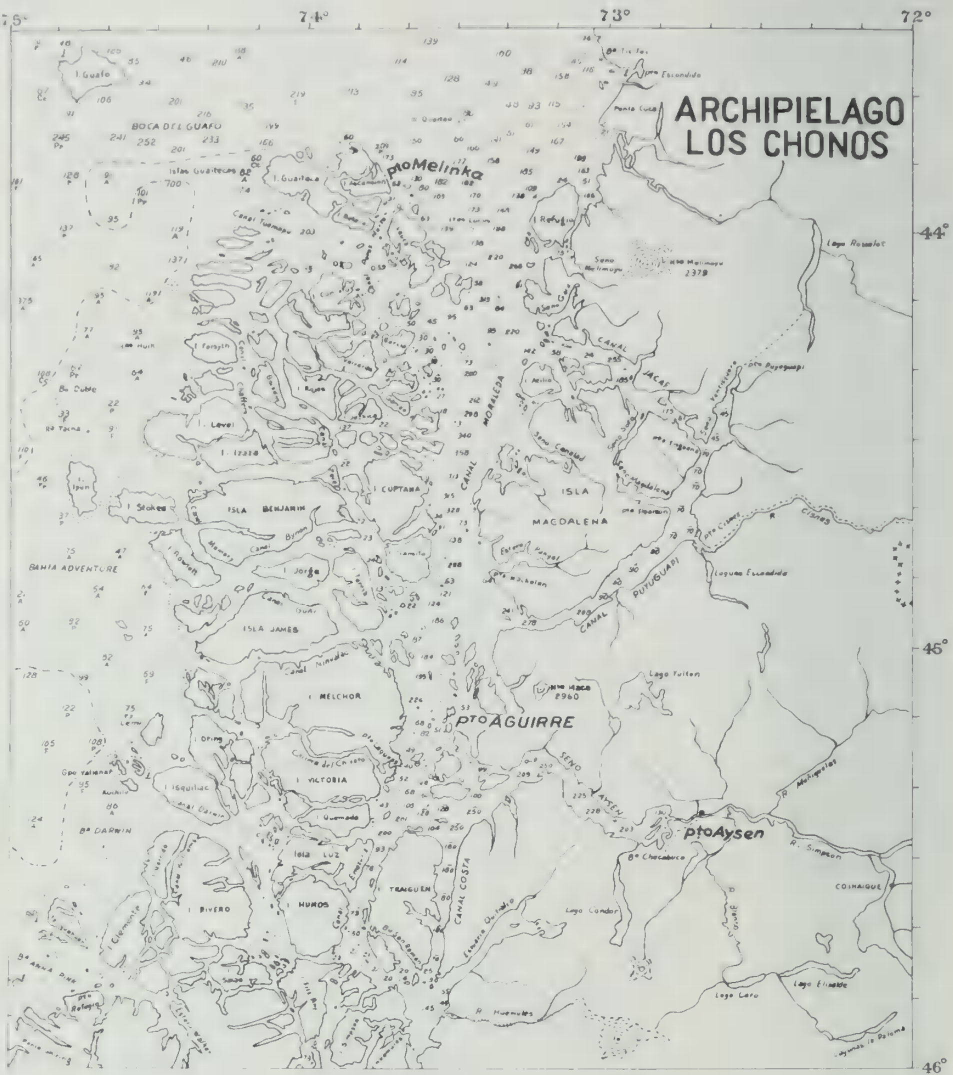
The first wave arrived at 1710 at Melinka, almost two hours after the earthquake. Some material damage was produced by the inundation of several houses, among them the office of the *Alcaldía de Mar* (equivalent to harbor master). No estimation of the height of the first wave was made.

At 1720, the effects of this wave were noted in Puerto Aguirre, where it was estimated that it reached a height of a little more than 3 meters above the level of the sea. At 1730 the wave arrived at the mouth of Rio Aysen (figure 3), where, according to estimates, the water rose 3 meters above the average level of the sea. The calculation is based on the fact that the wave arrived at the time of low tide and succeeded in inundating houses along the river banks above the level of the highest tides. Ten minutes later, the effects of this wave were felt in Aysen, reaching a level of 1 meter above the average. Water rose as in a very rapid tide, producing an inundation without breakers.

The second wave arrived at Aysen at 1900 hours, 1 hour and 20 minutes later. The height of this wave was estimated at 1.60 meters at the bar at the mouth of the Rio Aysen and at 0.8 meter in the port. The third wave arrived at Aysen at 2300 hours, 2 hours later, but was not observed at the bar because everyone had been evacuated by the motor ship Sebastiana.

A look at the map (figure 2) permits an appreciation of the canals through which the wave had to go and the great number of islands that were affected. No more information exists for this practically uninhabited area.

Between Melinka and Puerto Aguirre, separated by some 77 miles in a straight line, the wave raced with a velocity of approximately 460 knots. This value should be considered with reserve, because the hour in which the wave arrived at each one of these ports is only approximate. But in any case its velocity was considerable.



Departamento de Navegación e Hidrografía 1961.

FIG. 2. Sketch Map of the Archipelago of the Chonos.

The 42 miles between Puerto Aguirre and the bar at Rio Aysen was covered by the wave in about 10 minutes, giving, at the very least, a velocity of 250 knots.

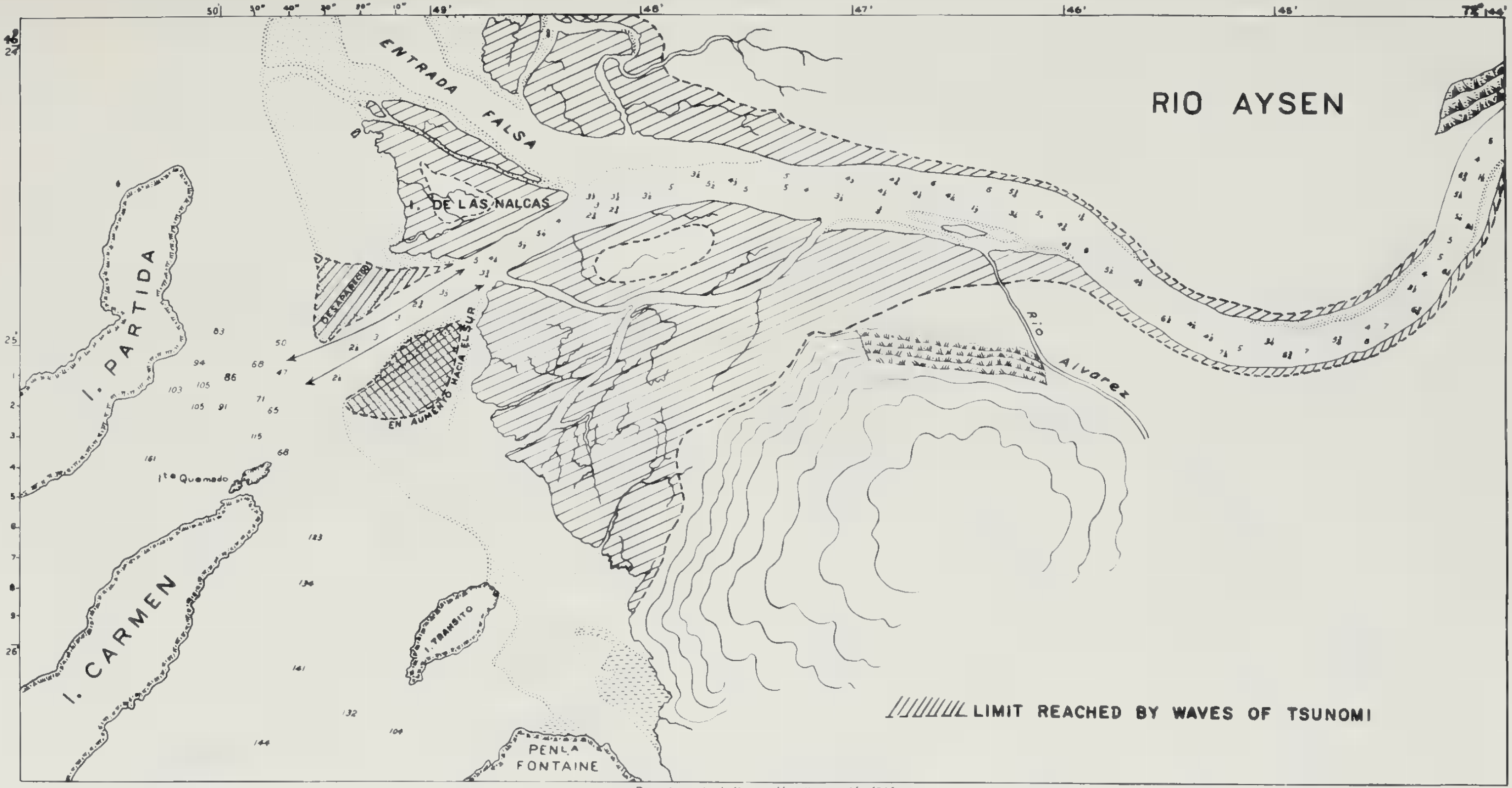


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FIG. 3. Changes at the Mouth of Rio Aysen. The dotted area indicates sand bars; the hachured region north of the river, land that has disappeared; the crosshatched region to the south, accumulated sand. Soundings are pre-earthquake.

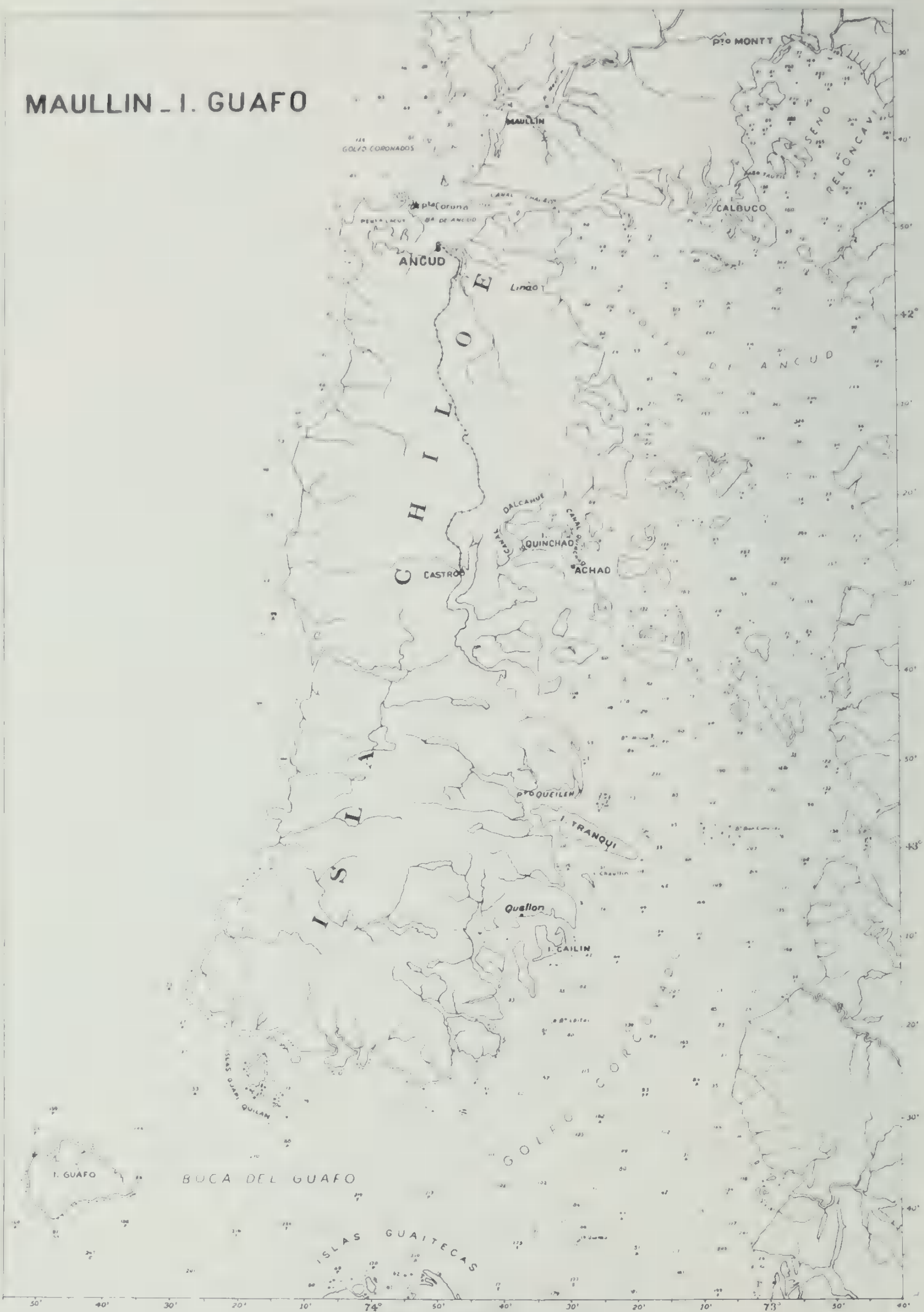

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FIG. 4. The Island of Chiloé and Vicinity.

The 7 miles from the bar at Rio Aysen to Puerto Aysen was run in approximately 10 minutes. This would give a velocity of about 40 knots. The average depth of the Rio Aysen is 6 meters, but at the bar its depth is not in excess of 3.5 meters.

On the map of the mouth of the Rio Aysen (figure 3), we have crosshatched the inundated zone, and the changes suffered by the sand banks have been indicated when they could be determined. The map of the Rio Aysen is not completed because the zone inundated along the river banks was very small.

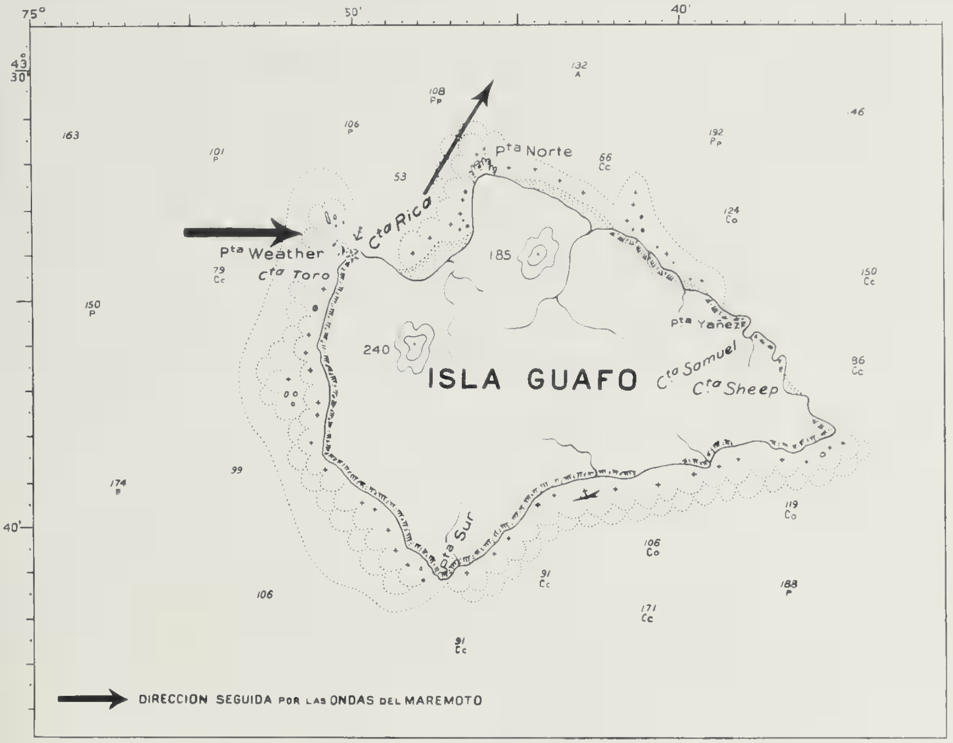

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FIG. 5. The Island of Guafo. Arrows indicate the directions taken by the first advance of the tsunami.

Soundings over the river bar indicate the depth has increased about 0.5 meter and the point south of the port bank has disappeared. On the other hand, the starboard bank has increased. It is probable that the alteration of the banks was due to a combination of the forces of the earthquake and the tidal wave. The earthquake could have brought about a settling or compaction of the sediments and the tsunami a redistribution of the sand, sweeping away a part of it and carrying the rest toward the south.

According to information from the Maritime Authority of Aysen, the banks of the river there have not undergone changes with respect to the average level of the tide.

Isla Guafo: The Island of Guafo, situated 20 miles to the south-southwest of Isla Chiloé (figure 4), consists of forested hills. The coast around practically all its perimeter consists of banks 60 to 100 meters in height. The lighthouse of Guafo is on Punta Weather (figure 5) 146 meters above the sea.

About 10 minutes after the earthquake, the personnel of the lighthouse saw that the sea was retiring slowly toward the west leaving about 600 meters of the sea floor exposed to view. At the same time that the sea was receding, a big wave was forming to the west of the lighthouse. This wave soon advanced upon the island with great velocity.

The first wave was followed by three other large waves before the phenomenon began to decline. The waves reached the greatest height inside Caleta Rica (figures 5 and 6), and their direction was from west to east. After striking the coast of the islands, waves were reflected toward the northeast.

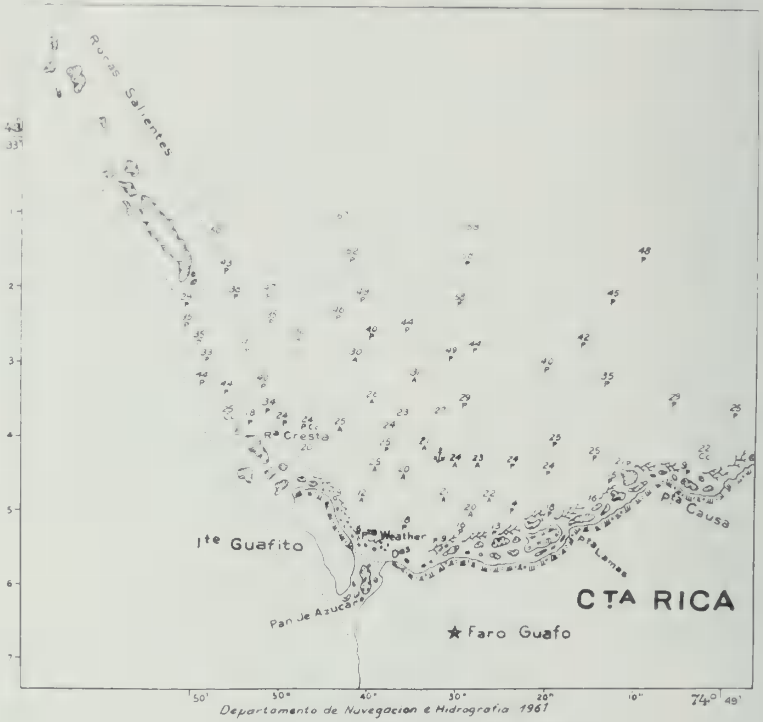

FIG. 6. Detail of Isla Guafo, Showing Isla Guafito and Punta Weather. Guafito is now connected to Guafo by dry land.

Two days later, the personnel of the lighthouse went to inspect the cliffs and were able to observe that the water had reached a height of 10 meters.

As a consequence of the earthquake, Isla Guafo was raised 3 to 4 meters. This is made evident in two ways: First, the old dock area, consisting of a rock with a flat upper part, is now useless because it has been raised to a greater height over the sea and is now surrounded by outcrops of rocks that were previously deeply submerged. Second, the Island of Guafito (figure 6) is now joined to the main island by a beach some 40 meters wide that is not covered by even the highest tide.

Quellón: Information concerning this port, situated at the extreme southeast of the Island of Chiloé, is very scarce (figure 4 and 7).

About 5 minutes after the earthquake, the sea retired some 50 meters and then began to rise slowly, arriving at its maximum 7 hours later. There never was much wave action and it appears that the rise of the water obeyed the tides and was more like a tide than a maremoto. The water inundated houses along the Avenida Costanera. In one zone, the sea rose about 22 meters and was detained by a high wall; in another, it reached 150 meters.[1]

The most noticeable effect was that after the earthquake the tides reached places they had not reached before. Based upon this and other observations, it is calculated that this part of the island experienced a sinking of about 2 meters. Figures 8–13 show the height reached by the tides on 4 and 5 August 1960, the day in which the highest tides of the year are produced along this part of the Chilean coast.

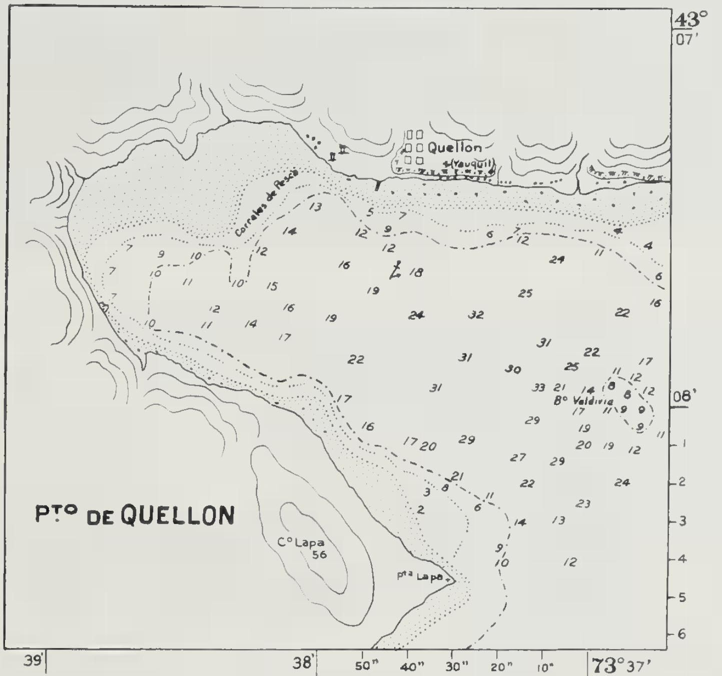

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FIG. 7. Detail of the Port of Quellón.

Achao: In Achao (figure 4 and 14), the tidal wave began about 5 minutes after the earthquake. The water seemed as if it were boiling, and it formed several currents that whirled through the Dalcahue and Quinchao canals. Some moments later, a wave seen forming about a mile in front of the port began advancing toward the coast. Two more waves formed in approximately the same area a little later and followed the first one in. The third wave arrived with the greatest force, but it did no damage because the earthquake occurred at about the time of low tide. The

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[1] Translator's note: This is probably a horizontal advance.

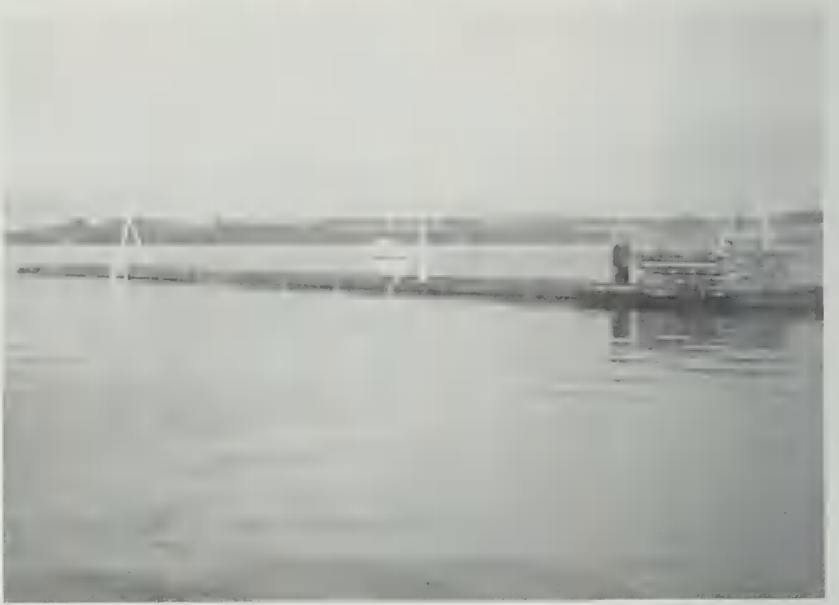

FIG. 8. Partial View of the Dock at Quellón Just before High Tide, 4 August 1960.

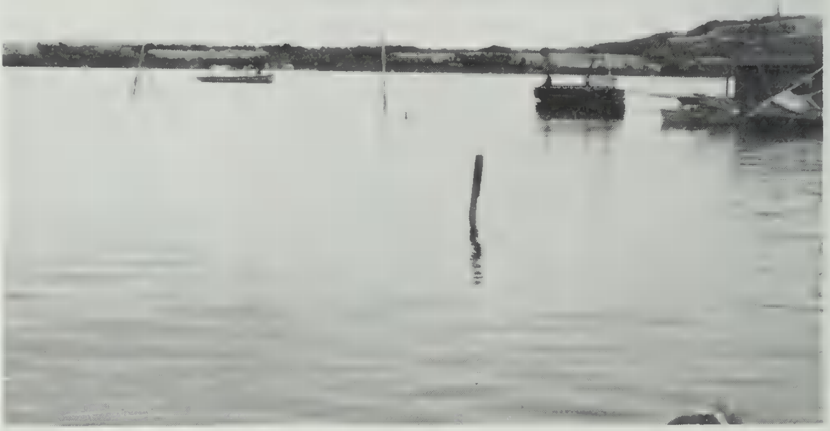

FIG. 9. Dock Shown in fig. 8, below Water During High Tide, 4 August 1960.

water of the third wave reached the line of ordinary high tides. The inhabitants of Achao estimated the height of the wave as about 2.5 meters.

There was not much accord between the people interviewed in Achao as to whether the first effect of the sea wave was a rise or a withdrawal of the sea.

As in Quellón, it is certain that the Island of Quinchao, where the port of Achao

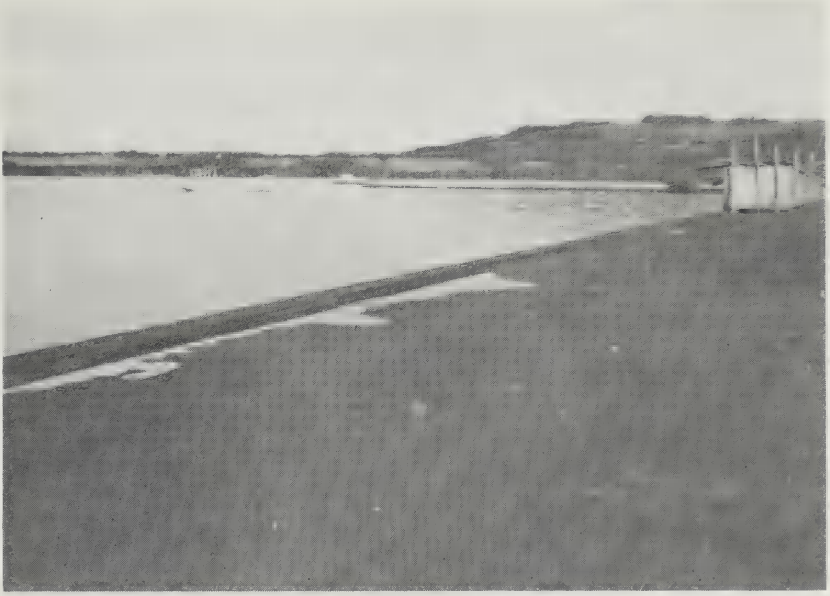

FIG. 10. Waterfront Street in Quellón before High Tide of 5 August 1960.

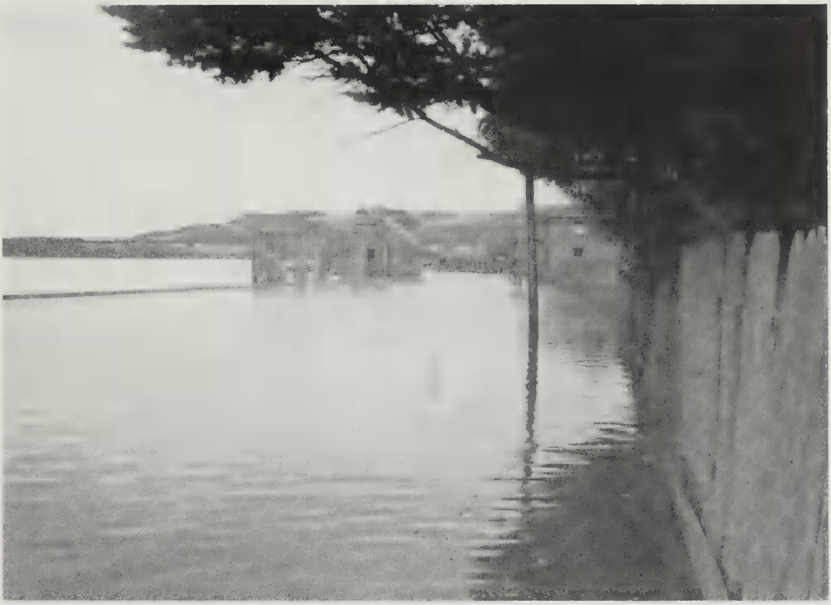

FIG. 11. Street Shown in figure 10. The tide of 5 August 1960 is still rising. The half-demolished building was the City Hall.

is located, sank. The actual amount of sinking has not been estimated, but evidence of sinking is clear. Before the earthquake, the port was surrounded by a beach about 300 meters wide. The beach is now only about 200 meters wide. The tides at syzygy inundated parts of the waterfront. Water reached the main street (figure 14), a

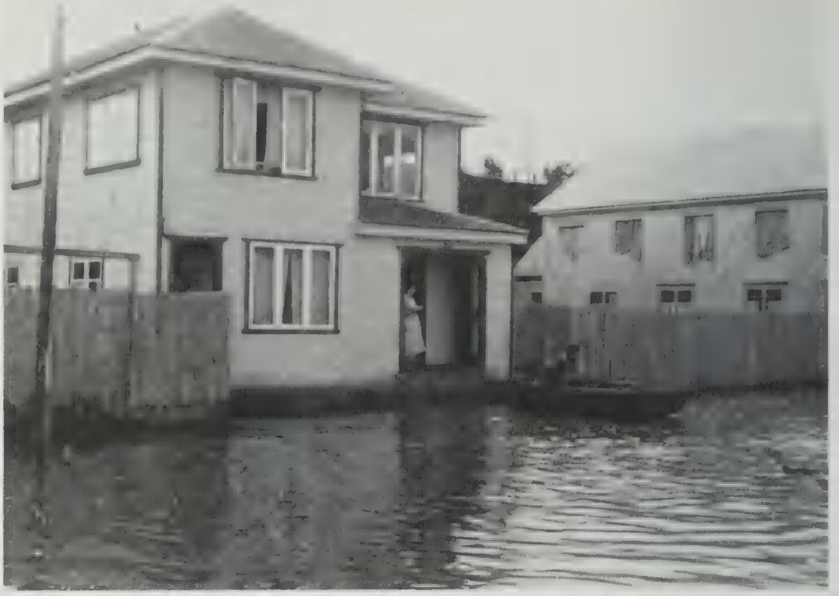

FIG. 12. House in Quellon on the Waterfront, During the Rising Tide of 5 August 1960.

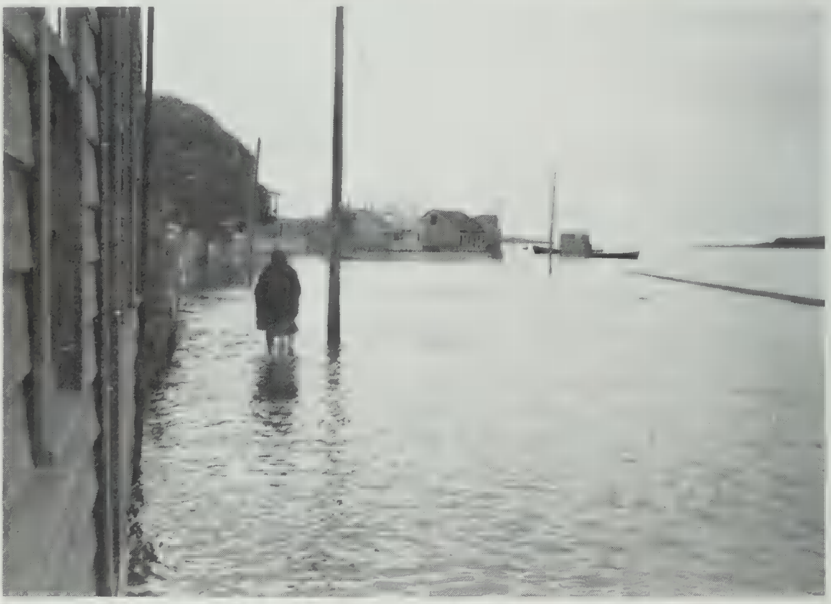

FIG. 13. Rising Tide on the Waterfront Street of Quellón, 5 August 1960. The sea wall is not quite covered.

thing that had never happened before. Some houses near the sea have had to be evacuated.

Linao. Information from this port is scarce (figure 4). About 10 minutes after the earthquake, the sea withdrew. Three waves were formed, with heights estimated at 0.5 meter.

After the earthquake, the tides reached zones to which they had not risen before, inundating the village at each syzygy. This is because of the sinking of the land brought about by the earthquake.

Calbuco: The information obtained from the port of Calbuco (figures 4 and 15) indicates that a tsunami was not observed in this area. After the earthquake, areas were inundated during high tides that had not previously been reached by the water. Sections of the beach, Surgidero La Vega, have sunk.

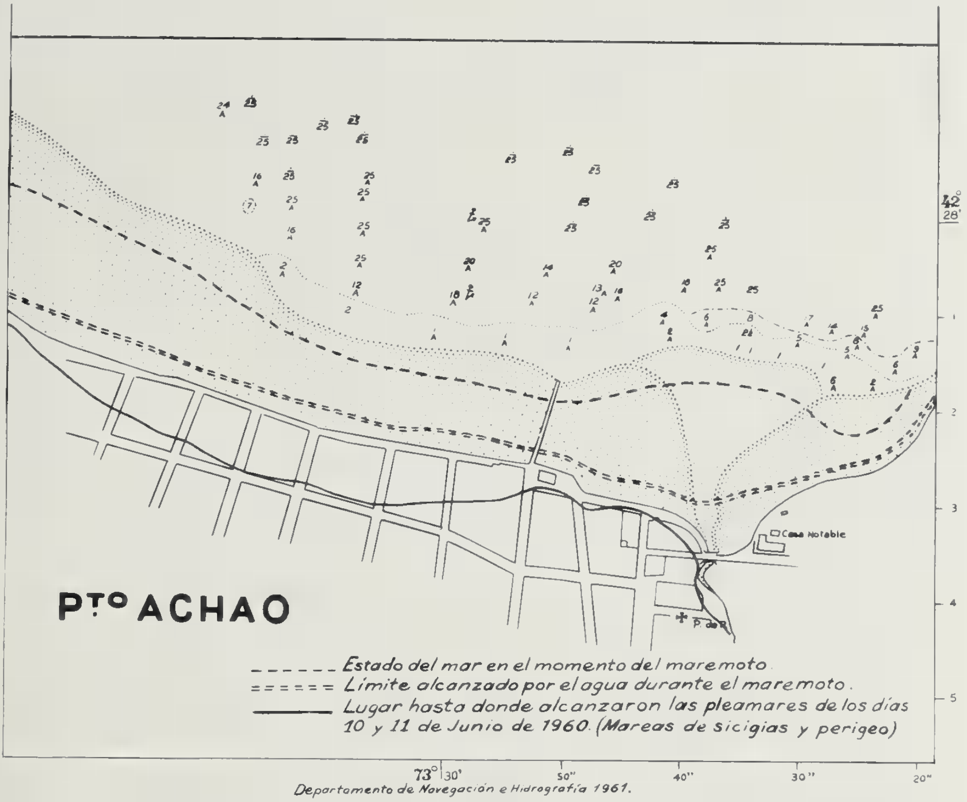
PTO ACHAO
Casa Notable
P. de
------ Estado del mar en el momento del maremoto
====== Límite alcanzado por el agua durante el maremoto.
—— Lugar hasta donde alcanzaron las pleamares de los días 10 y 11 de Junio de 1960 (Mareas de sicigias y perigeo)
42° 28'
1
2
3
4
5
73° 30'
50"
40"
30"
20"

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FIG. 14. Puerto Achao. Broken line indicates the state of the tide when the maremoto occurred; double broken line, maximum advance of the water during maremoto; heavy solid line, limit reached by the high tides of 10 and 11 June 1960. The former high tide line is just seaward of the shoreline.

Puerto Montt: Information obtained in Puerto Montt (figure 4) indicates that in this port neither a tsunami nor abnormalities in the tides were noted. A leveling, done by naval personnel, in the neighborhood of Angelmó demonstrated that the land in this locality suffered a descent of about 1 meter.

Ancud: According to information from the Captain of the Port of Ancud (figure 4 and 16), the first evidence of the tidal wave was an abnormal increase of water level of approximately 1 meter about 20 minutes after the earthquake. After this elevation of the water, the sea began to withdraw, first slowly, then rapidly. A current of great intensity was noted in the Gulf of Quetalmahue where water flowed from the west to the east out out of the gulf. The water then followed a course from south to north as the waters retired from the Bay of Ancud.

The withdrawal was enormous, leaving the bottom completely uncovered within the 5 meter contour. Farther out to sea, low spots were exposed to view, including several deeper places near the coast. It was not possible to establish precisely what the depth was at these points.

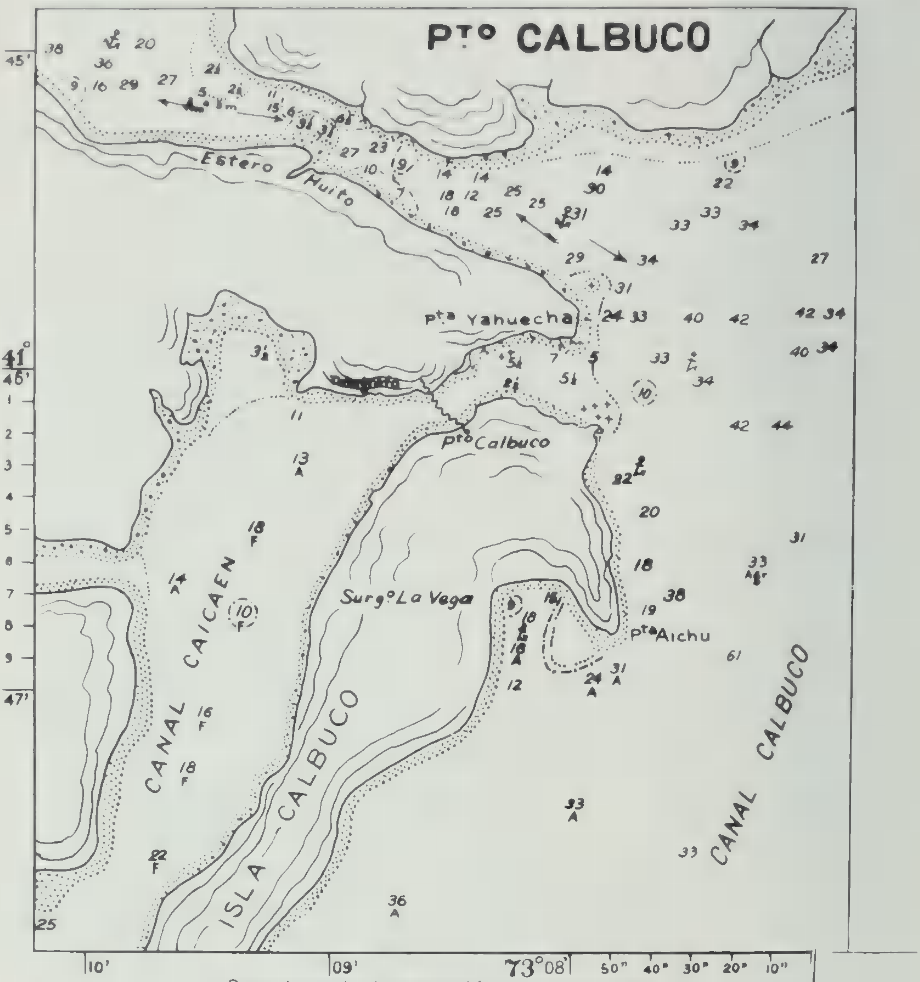

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FIG. 15. Detail of the Port of Calbuco. The beach at Surgidero La Vega has undergone subsidence of about 0.3 meter.

The coast of the Bay was struck 50 minutes after the earthquake by a great wave that formed in front of the Bay, in a locality not precisely determined. The direction of this wave was noted as being from north to south. The water that was retiring was absorbed, giving place to the formation of a single uniform mass of water that seemed like a wall. It was estimated that between the lighthouses Punta Corona and Punta Ahui this mass of water had a height of about 15 meters. This observation was made by several people, among them the master of a sailing ship that had been drawn away during the withdrawal of the sea, who at one moment compared the height of the mass of water with that of the mast of his ship.

In its advance toward the south, the wave struck with great force along the northeast coast of Península Lacui.

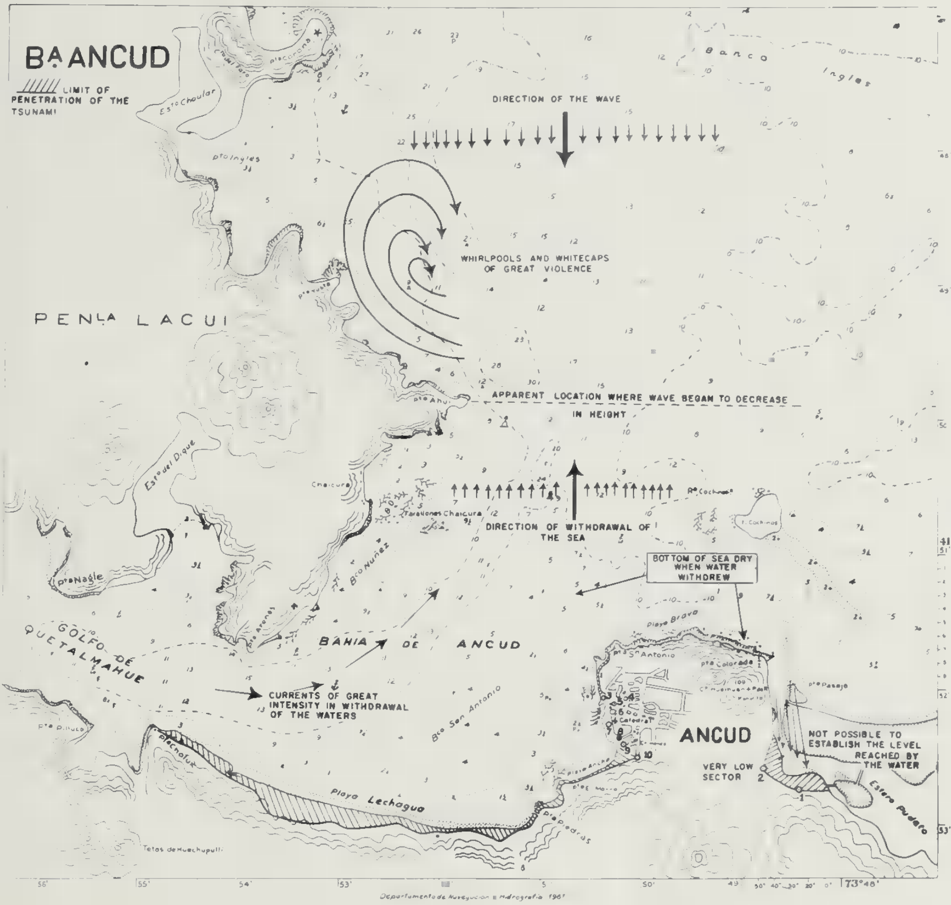
Bª ANCUD
LIMIT OF PENETRATION OF THE TSUNAMI
Banco Ingles
DIRECTION OF THE WAVE
WHIRLPOOLS AND WHITECAPS OF GREAT VIOLENCE
PENLA LACUI
APPARENT LOCATION WHERE WAVE BEGAN TO DECREASE IN HEIGHT
DIRECTION OF WITHDRAWAL OF THE SEA
BOTTOM OF SEA DRY WHEN WATER WITHDREW
GOLFO DE QUETALMAHUE
BAHIA DE ANCUD
CURRENTS OF GREAT INTENSITY IN WITHDRAWAL OF THE WATERS
ANCUD
NOT POSSIBLE TO ESTABLISH THE LEVEL REACHED BY THE WATER
VERY LOW SECTOR
Estero Pudeto
Playa Lechagua
Playa Brava
73°48'
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Fig. 16. Details of Tsunami in Ancud Harbor.

In front of Punta Ahui, it was noted that the height of the wave began to diminish to approximately 5 meters as it struck violently against the coast of the Port of Ancud. The violent accumulation of the waters in the Port made it seem that these were displaced following a curve first to the west, then east, south, and north. The wave also penetrated Estero[2] Pudeto, but with less intensity because Isla Cochinos protected its entrance.

Later, in the time between the arrival of this great wave and 1700 hours, three more waves of lesser intensity and force reached the coast. These were more or less like rises of the sea caused by an abnormal augmentation of the water.

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[2] *Estero* is a Chileanism loosely used to designate fiords and inlets.

In fig. 16 we have marked the diverse points that were inundated and have delineated the maximum height reached by the water along the coast from the Bay of Ancud to Estero Pudeto. On the chart of the city, points are marked on the streets at places where the sea reached its maximum penetration.

The greatest distances are represented by points 4 and 10, corresponding to a street with a height of 1.5 meters above the level of the dock, and to a sector that is now below the level of the sea, respectively. The height at the head of the dock is actually 4.7 meters above the average level of the sea. This should give a penetration of the water to a point located more than 6 meters above mean sea level.

In the places between points 4 and 10 the water covered less distance owing to blockage by buildings in the low parts and by a wall formed by the hills that are located a short distance from the seashore.

On the coast south of the Bay, the sea covered a great extent because of the width of the beaches in this region. The water reached the foot of the hills, which here rise vertically.

On the southern and western coast of the Gulf of Quetalmahue, as much as in the northern part, the water rose without force about 1.5 meters.

Along the coast between the lighthouses Punta Corona and Punta Ahui, and along the northern coast of the city between Punta San Antonio and Punta Colorada, the sea struck with the greatest violence, but because the coast was high the waters only inundated the beaches and the low sectors.

In Estero Pudeto, the water reached the sector indicated in figure 16. The points indicate places where it has been proved authentically that the water reached. In the river itself the sea inundated a great zone of the bank east of the mouth, as marked with arrows on the map.

The waters also covered a great extension of the north coast of the Pudeto. The inundated area cannot be precisely established and for this reason it has not been marked on the map. The Pudeto area and the mouth of the Estero received the effects of the sea wave in an attenuated manner, as has already been mentioned, because of protection given by Isla Cochinos.

In the zone, located between points 5 and 10, of the plain formed by the lowlands, including lands below mean sea level, and by beaches, there existed the suburb of La Arena, composed of numerous wooden houses that were totally washed away. On the other hand, a wooden house situated approximately 25 meters from the shore and 1 meter above the level of the sea did not suffer damage but was protected from the beating of the waves by several pine trees planted in front of it.

It is possible to state that the water of the Bay of Ancud and the surrounding zones is now 1.2 meters higher than before, which is clear evidence of the sinking of the zone following the earthquake. The observations conducive to this conclusion are the following:

(a) The water now covers the beaches and the low sector of the coast to a greater depth than the high tide did before the earthquake.

(b) Ships up to 25 tons now tie up at the sea wall in the sheltered part of the harbor when the tides permit; this was formerly impossible even at syzygy.

(c) The tides of the syzygies during July and August (the highest in 1960) reached the lower part of the town, especially in the vicinity of the Port.

Some other observations worthy of note are numerous small landslides around the Bay and changes in Estero Pudeto. The bar of the Estero is much less dangerous than before because the Estero is deeper and its mouth is wider. The lowlands of its banks are completely covered by water.

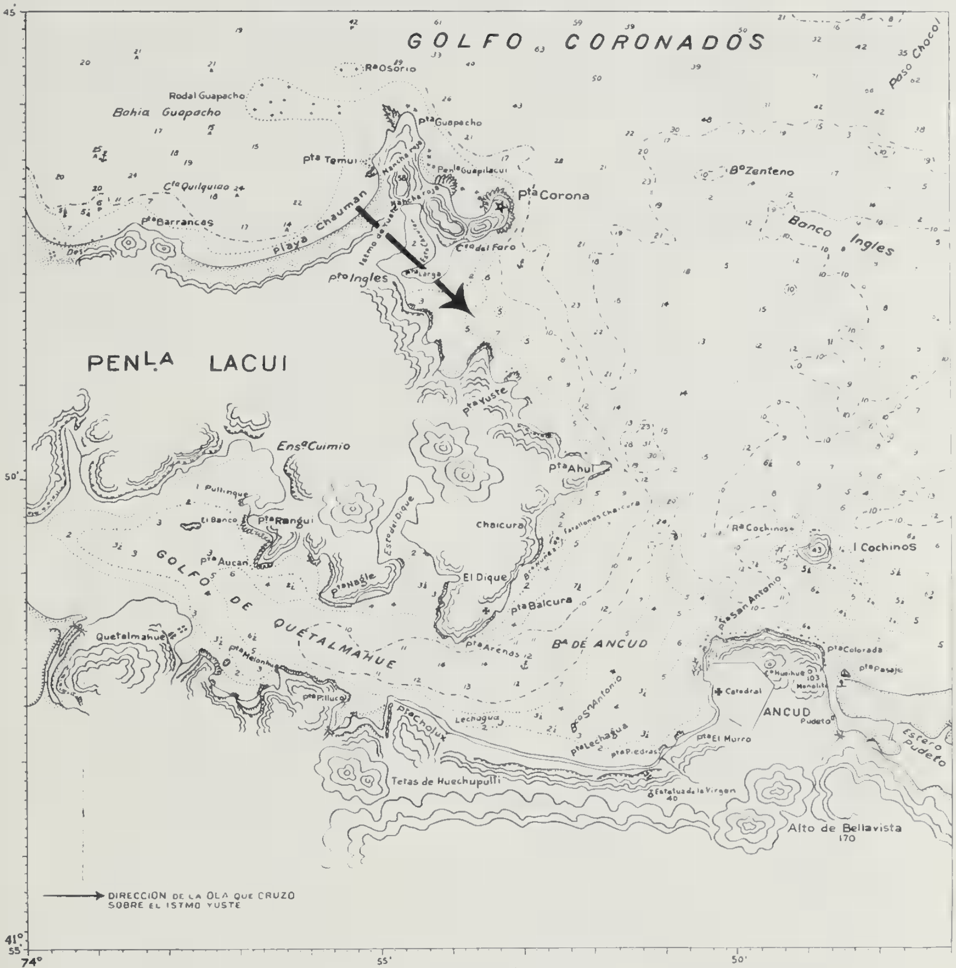

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FIG. 17. Localities Near Ancud Including the Isthmus of Yuste and Playa Chauman.

Punta Corona Lighthouse: The Punta Corona lighthouse is situated on the north coast of the Island of Chiloé, upon a hill 66 meters in height (figures 4 and 17).

Because of the earthquake the tower of the lighthouse fell and the chief of the lighthouse, Sr. Gabriel Jimenez, his family, and the rest of the personnel, were obliged to leave the vicinity of the buildings in case the antenna towers of the radio station should fall. Upon leaving the buildings they went westward down the hill so that they lost sight of Golfo Coronados and of the entrance of Canal Chacao, but they were able to see what happened in front of Playa Chauman (figure 18).

Between 8 and 10 minutes after the earthquake they noted that the sea had begun to withdraw slowly from the beach, leaving about 500 meters of the bottom uncovered. This process lasted about 10 minutes. Together with the withdrawal an enormous wave some 15 to 20 meters high was forming approximately 800 meters from the coast. In front of this wave smaller waves very similar to boiling water were observed (figure 19). The wave while forming gave the impression of being detained. This is certainly due to the fact that while the wave continued forming,

Fig. 18. Hills at Punta Guaspacho and Playa Chauman before Tsunami.

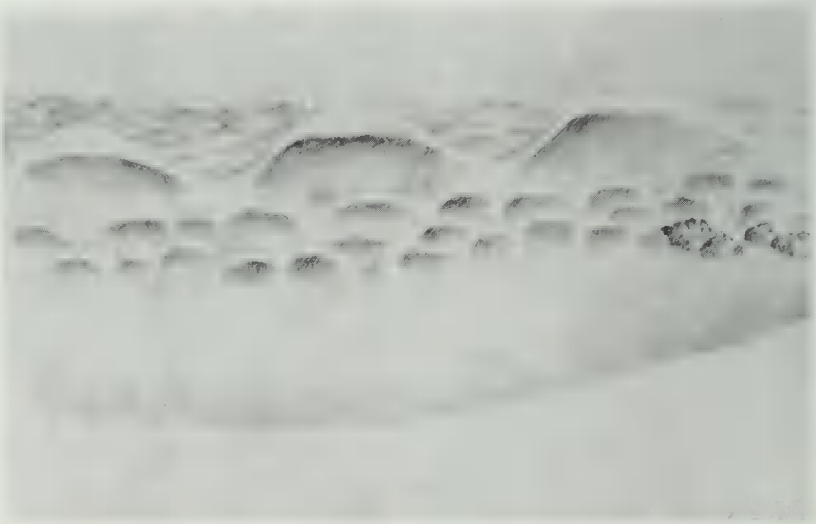

Fig. 19. Artist's Conception of the First Great Wave as It formed before Playa Chauman.

it was impossible to appreciate the extent from the land. Soon this veritable wall of water advanced with great velocity and great force in the direction of the coast. It passed over the Isthmus of Yuste across Estero Chaular, sweeping away the part of península Punta Larga de Chaular that closed the Estero on the southeast, then penetrated through the gap of Puerto Inglés, and continued through Golfo Ancud toward the sea. In its passage over the Isthmus of Yuste it washed away some houses that were there and all the small ships that it encountered in its passage (figure 20). The water had not totally retired when a second wave of lesser height formed in approximately the same place as the first, but it did not succeed in crossing over the Isthmus. Sr. Jimenez could not tell if a third wave was formed, but in any case he was able to establish that the sea maintained its abnormal conditions for several days. Subsequently he established that the present amplitude of the tide is much less than before the earthquake.

FIG. 20. Height of Water as It Inundated the Isthmus of Yuste and Playa Chauman.

Generalities about the Zone of Chiloé: From the soundings and hydrographic reconnaissances made by Navy ships in the zone of Chiloé (figure 4) it may be stated that all the canals suffered alterations in depth as a consequence of the earthquakes, having been subjected to a general augmentation of depth caused by the general sinking experienced in the zone of the south of Chile.

It may be stated also that the tidal currents increased their velocities, expecially in Canal Chacao, Paso Tautil, and the entrances to Quellón. A detailed description of the changes in the regime of the tides of this zone is found in Part IV.

Maullin: In Maullin (figures 21 and 22) the maremoto occurred about 20 minutes after the earthquake. The first evidence was a withdrawal of the water followed by 8 sizable waves of which the second and the fourth were the highest. Their height was estimated at 14 meters. The waters penetrated deep into the interior and the waves were propagated upriver with great force, destroying all that they found in their path. The land has sunk; the town of Quenuir and the lower part of Maullin are now covered by the sea. In the map (figure 22) we were not able to indicate in detail the inundated zones because good data are lacking.

Caleta Mansa: The maremoto began in Caleta Mansa (figures 21 and 23) 15 minutes after the earthquake, in the form of a wave 8 meters high followed by two more waves, at intervals of 10 and 15 minutes, of progressively greater height. The second wave had a height of approximately 10 meters and the third was estimated at 12 meters. After the phenomena had begun to decline, abnormal sea conditions continued for several days.

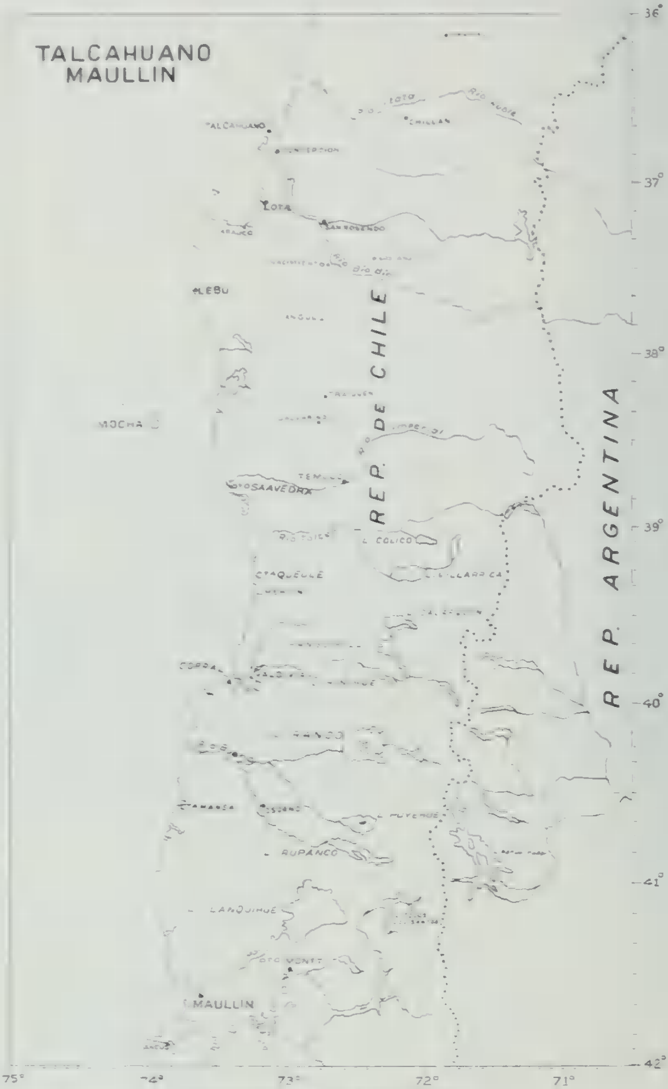

FIG. 21. Localities Between Ancud and Talcahuano.

The waves had the greatest heights at the entrance to the bay and were described

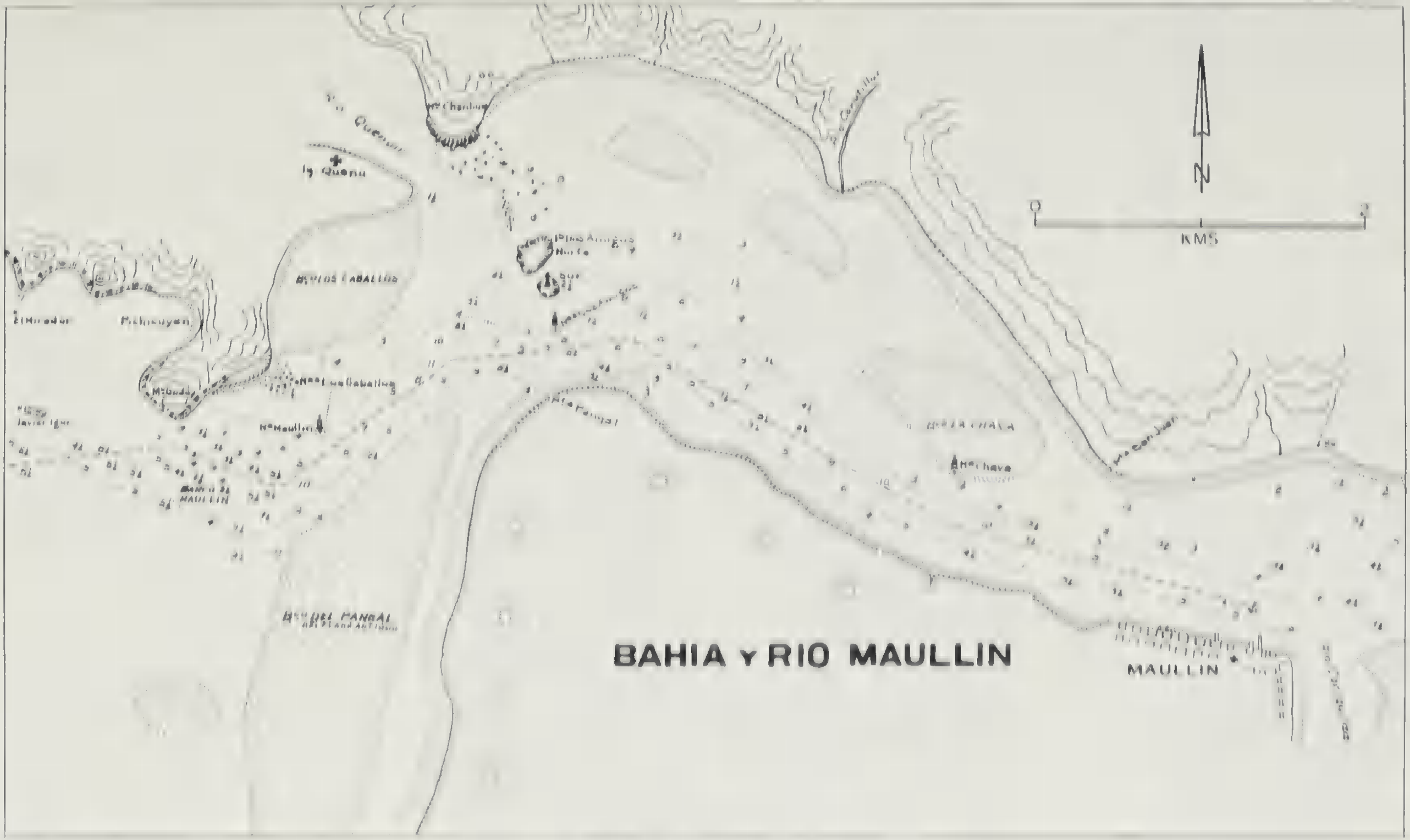

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FIG. 22. Details of the Bay and River at Maullin

as avalanches of water without breakers. The third wave passed over a warehouse whose highest point was 12.5 meters above the level of reduction of the soundings (the amplitude of the tide in Caleta Mansa is 1.8 meters).

In general the flooding experienced was scanty because the coast along the bay is steep. The extent of the inundation is indicated in figure 23.

At the time of the earthquake the motor ship ISABELLA had just begun to take on cargo, when the water began to rise because of the first wave. The cables were cut so that the ship could leave the port. The stevedores aboard the ship remained aboard, while the others, on the dock and on land, ran with their families to nearby high places. Because of the rapidity with which this was done no lives were lost. The motor ship ISABELLA succeeded in leaving the Caleta after having been aground for some minutes because of the withdrawal of the water after the first wave.

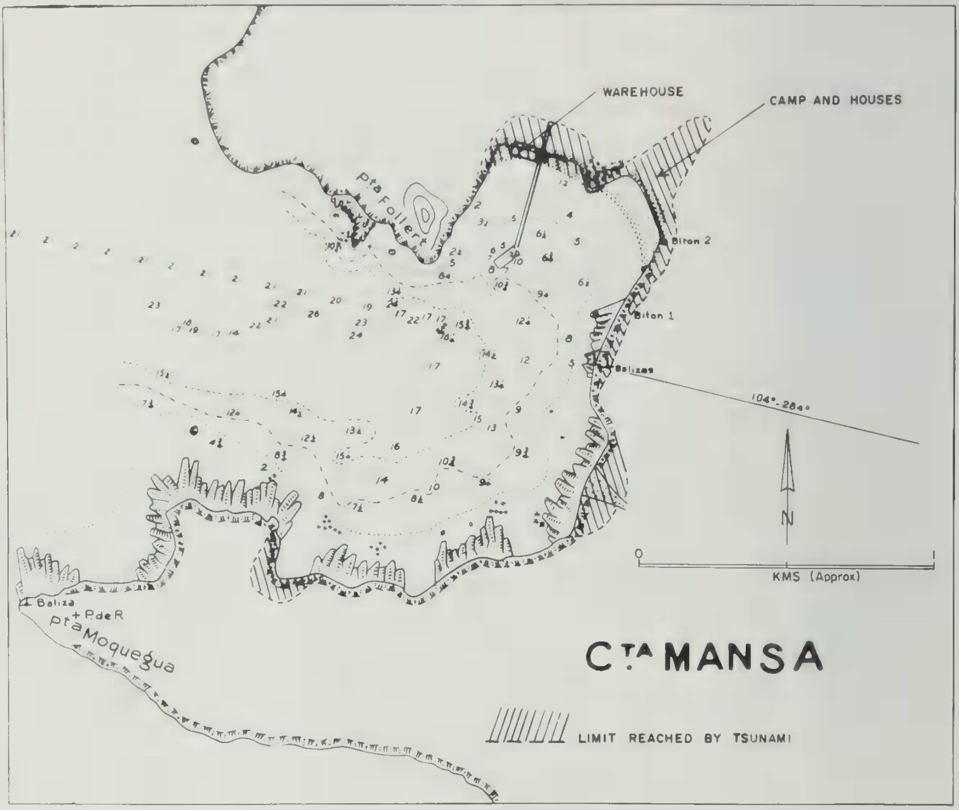

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FIG. 23. Details of Caleta Mansa ("Quiet Harbor").

One could observe from the hill up which the people had climbed that the waves penetrated inside the bay and then withdrew, tearing up and washing away the houses, trees, and 50 meters of access to the dock (figure 24).

During the withdrawal of the water, a great part of the bay was dry. The head of the dock, in 8 meters of water (referred to the level of reduction of the soundings), was left high and dry three times. It was observed that at the time of the greatest withdrawal, between the second and third waves, the water withdrew some 200 meters farther out.

The following day, Caleta Mansa was sufficiently normal to permit the ISABELLA to enter and disembark the stevedores.

Later observations indicated that the head of the dock had resisted the pounding of the waves and the only destruction was 50 meters of the approach to the dock.

Vertical soundings made to verify possible changes showed that there were no variations in the depth of this bay.

Rio Bueno: In accordance with observations made by the A. P. Piloto Pardo, which made soundings in the Bay of Dehui and over the bar in Rio Bueno (figure 21), it was found that the bar suffered some important changes. Before the earthquake, the depth (referred to the level of reduction of the soundings), was 3 meters above the bar. This increased to a minimum depth of 5.75 meters after the phenomena. The bar, even though diminished, still presents a hazard because one can cross only under certain circumstances and with the aid of a pilot. The river itself did not suffer variation except that in general it was found to be deeper than before. With the increased depth over the bar there now exists the possibility that this river way may again be utilized by boats of adequate size as far as Trumao or perhaps even farther.

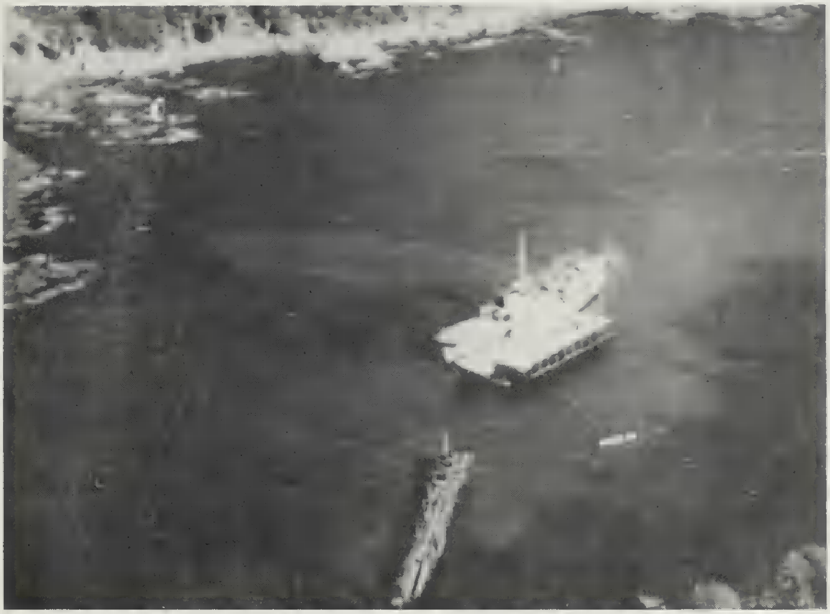

FIG. 24. Partially Destroyed Approach to Dock in Bahia Mansa.

Corral y Rio Valdivia: The Bay and Port of Corral (figure 25) is the place from which we have the greatest amount of information, because three ships of the Merchant Marine were anchored in the port and suffered the terrifying effects of the maremoto. These ships were the CANELOS, CARLOS HAVERBECK, and SANTIAGO, the first two of which were lost. Information is also available from the people who observed the phenomena from land and in the reports from the maritime authorities.

The tidal wave was very complex because of the Rio Valdivia, which empties into the Bay of Corral. The information collected coincides in general and there are only discrepancies in certain details. So that the descriptions of the effects will not be too confused, we will consider first a general narrative of the phenomena; second, that which happened as seen from the land; third, the adventures of the ships; and fourth, the changes in the Bay.

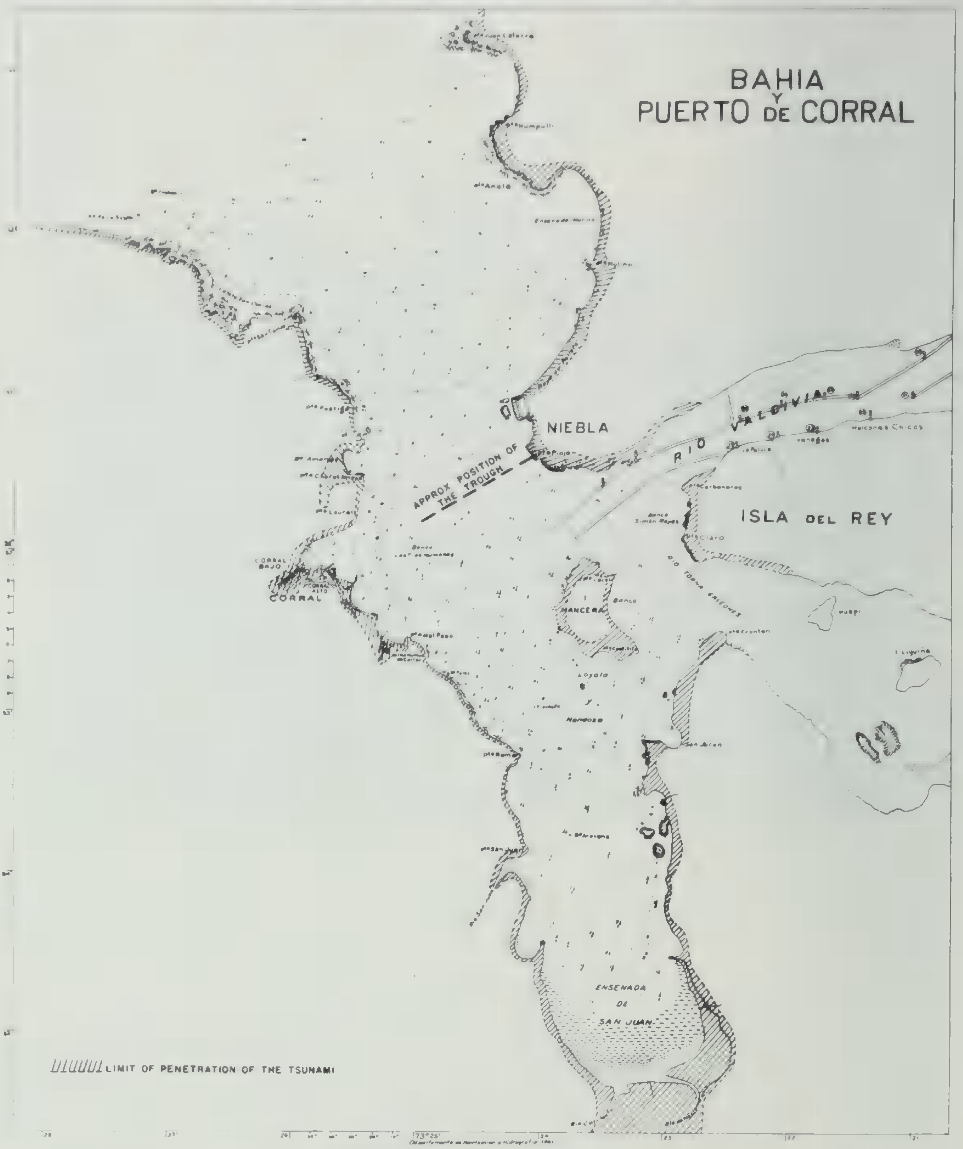

FIG. 25. The Bay and Port of Corral.

The earthquake, observed as a movement from the northwest to the southeast, was felt aboard the ships with great violence. The ships bucked and the masts and rigging swayed, giving the impression that they were going to break. In the CANELOS a pile of sacks fell over. The movement was similar to a violent full speed astern at full power.

In the Port of Corral almost no destruction was caused by the earthquake. In the high part there were some cracks in the ground that caused more alarm than damage. On the other side of the Bay, in Niebla, there was more destruction, and a great landslide in the vicinity of Faro Niebla was observed and heard. There was great damage in the old Fort Niebla.

While the earthquake was going on, it was noticed that the sea began to bubble exactly as if the water were boiling. Then the ships began to bob about because of small horizontal movements of the water. Small whitecapped waves formed but did not break.

Some 10 minutes after the earthquake, Sr. Harold Weller, second pilot of the CANELOS, who found himself in charge of the ship, saw that the level of the sea was going down slowly. He estimated that it went down 1 meter or more in about 2 minutes. This movement, it appears, was noticed only by this official; nobody else mentioned it. The pilot asserted, however, that he had not been fooled because he could see quite clearly from where he was. A little later, about 1525, the Bay commenced to fill slowly, and currents of increasing strength began to form, constantly increasing in velocity also. All around the buoys whitecaps were formed by the velocity of the water. First to be submerged was the dock of a canning company located at Punta Laurel. A little later the water began to pass over the passenger dock. The first houses of the street between Corral and Amargos were washed from their foundations and collapsed, as were the first houses of the suburb of Corral Bajo (figure 25). The water continued to rise, inundating the first floors of the houses on Sixth of May Street, the principal street of the Port, located near the waterfront (figure 26). A school situated at the beginning of the road to Amargos was inundated to the eaves. In the first wave, the water reached a height estimated at 3 to 5 meters above sea level.

At approximately 1550 hours, the level of the water began to go down, first slowly and then with great rapidity. The outgoing water carried a great many houses and the ships CANELOS and CARLOS HAVERBECK out to sea. Soon the beach of Corral began to dry and then the water withdrew some 30 meters horizontally from the fill of this Port.

At 1625 hours, a great mass of water entered the Bay in a gigantic wave that formed slowly in front of the Bay and was described as "A great wave of overpowering force that destroyed all that it encountered in its passage, such as docks, buildings of concrete and wood, and installations built of steel reinforcing such as the substation of the electric company and the Altos Hornos factory." (figures 27–29). The most exact estimation of the height reached by the water in this second or in the third wave, the other big one in Corral, is 8.5 meters, in spite of information that it produced damage at places up to 10 meters above the level of the sea. It is very difficult to establish whether the second or the third wave was the highest, since it appears probable that these waves were very similar in amplitude.

The inundation produced by the second wave held stationary for several minutes

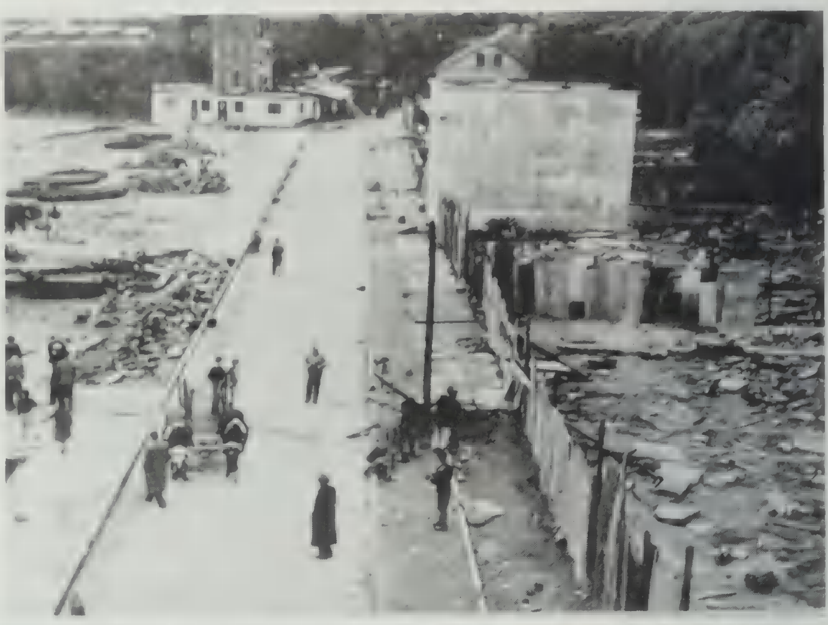

FIG. 26. Sixth of May Street (Main Street of Corral) Following the Tidal Wave (W. Weischet photograph).

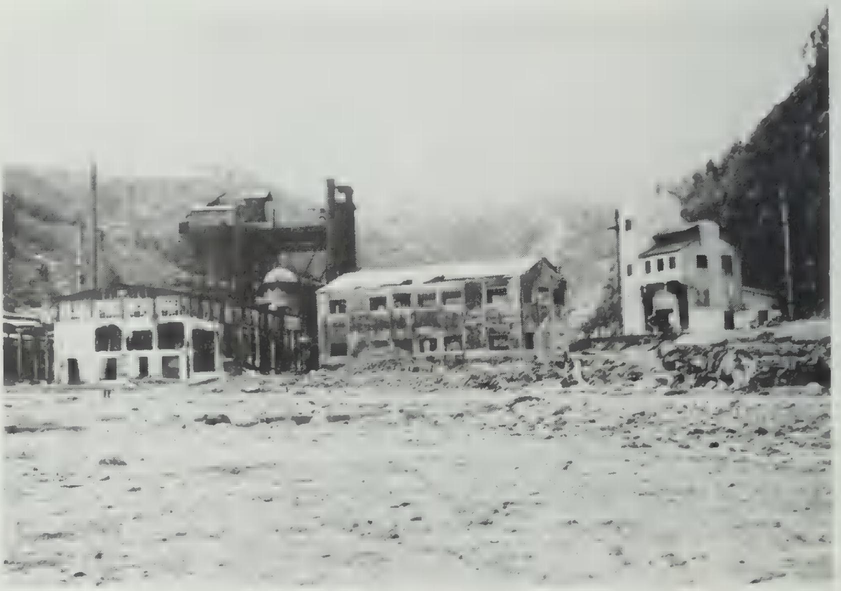

FIG. 27. The Foundry "Altos Hornos" of Corral after the Tidal Wave.

and then began to recede, slowly at first and then at a velocity approaching 15 to 20 knots. This withdrawal of the water carried away all of the settlement of Corral Bajo, part of Corral Alto, the lower parts of Niebla, and other settlements constructed on terranes less than 10 meters above the mean sea level.

Ships were carried away, pounded against the coast, and grounded, as will be

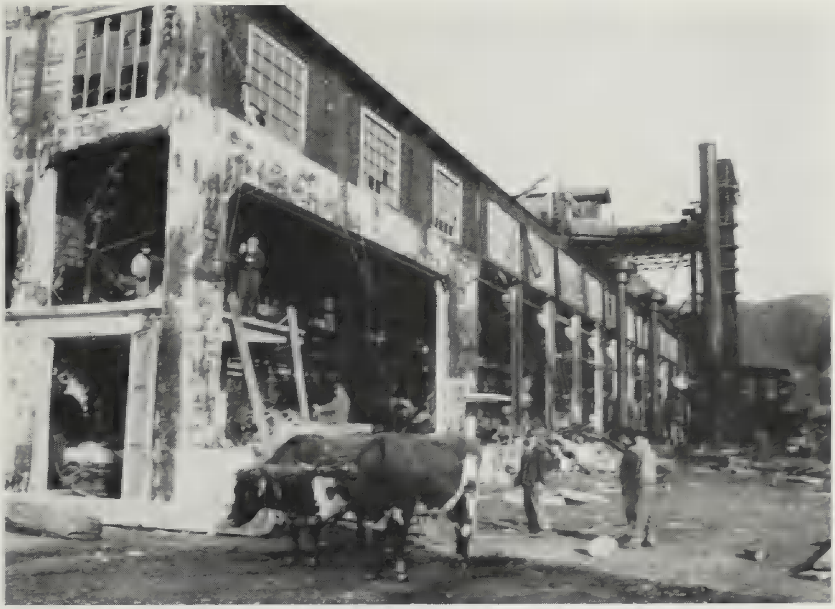

FIG. 28. Detail of the Destruction in the Building at Left in figure 27 (O. Arrigada photograph).

FIG. 29. Detail of the Damage to the Warehouse in Extreme Left of figure 27 (O. Arriagada photograph).

described in more detail later. While the water was retiring, a strange graben, or depression, in the water surface formed between Banco Tres Hermanas and Punta Piojo (figures 30–32). The phenomenon was clearly seen from the CARLOS HAVERBECK, which was tied up over Banco Tres Hermanas, and from the hills of Corral. According to the description by the witnesses, it appeared that the water coming from the interior of the Bay and from the River fell into a ditch or trough some 6 to 8 meters deep and about 10 meters wide, emerging in a turbulent form on the other side and continuing seaward. Two tugboats tried to escape in the direction of the River but were carried toward the trough. One of them, the PACIFICO, easily recognized by its white color, fell half astern and half abeam (figure 30) into the abyss, undergoing a double somersault before disappearing from view. Nothing more has been learned of this vessel; its remains have not been found. The owner of the PACIFICO was

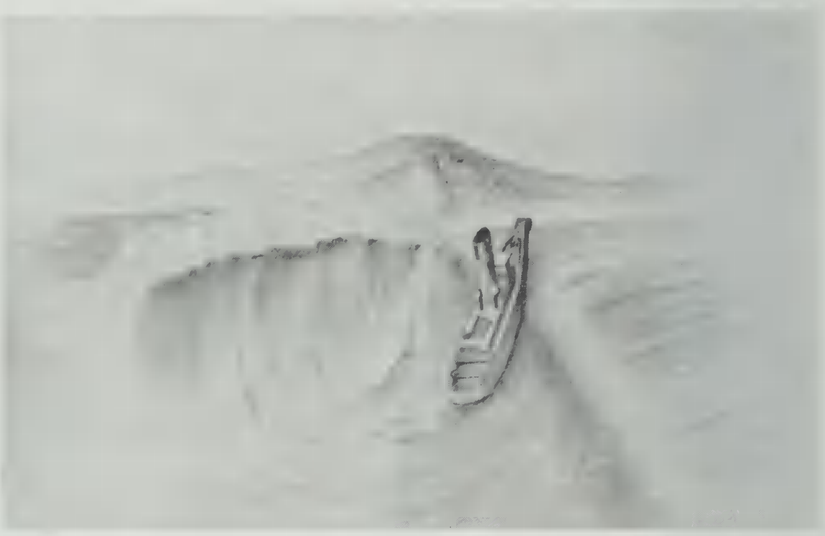

FIG. 30. The Tugboat EL PACIFICO Falling into the Extraordinary Trough That Formed Opposite Corral (Looking Toward Niebla). The tug has never been found.

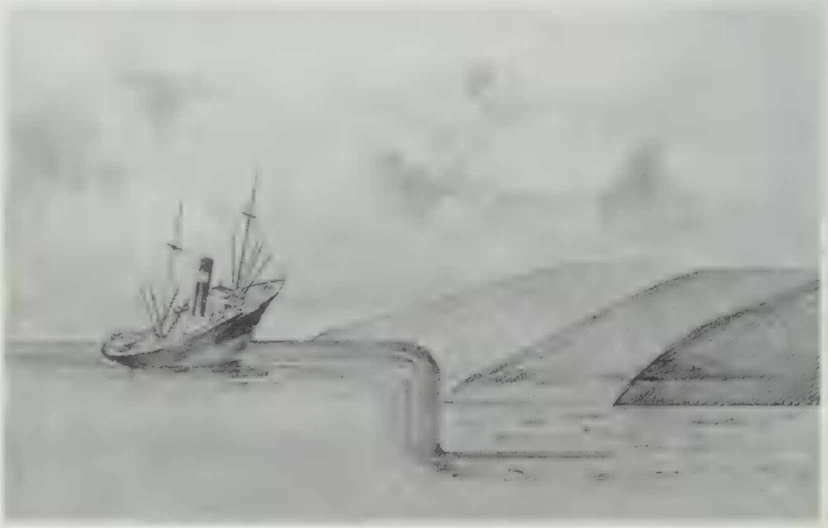

FIG. 31. A Cascade Formed on the East Side of Banco Tres Hermanas During the Greatest Withdrawal of the Water. The higher side is upstream.

miraculously saved, without being able to explain how. His last memory before regaining consciousness about 0.75 mile away, on a beach on Isla Mancera, was the fall into the abyss while the boat was capsizing. The other tugboat, PUMA, was also drawn toward the trough, but its master, with more presence of mind and perhaps having better engines, succeeded in turning his tug. Steering into the abyss at top speed, he was able to cross it. His passage across the trough was almost simultaneous with the double capsizing of the PACIFICO. A little later, the third wave caught the PUMA and carried it upstream, leaving it in front of Isla Mancera. The owner saw a possibility of salvation and, by taking advantage of the currents, succeeded in reaching shelter in Rio Tornagaleones, arriving the next day in Valdivia.

Witnesses calculated that the trough remained for approximately 15 of the 20 minutes during which the removal of the water lasted. The lowering of the water was considerable, leaving a great part of the Bay practically dry. The water rose 8.5 meters and it should have had a similar lowering, which would give an amplitude for a second or third wave of 17 meters. While the trough remained it was observed from the land that the water coming from the interior of the Bay and the River fell, forming a cascade 3 or 4 meters high on the west side of the Banco Tres Hermanas (figure 31), and that it was carrying millions of cubic meters of dirt and sand that had accumulated in the course of time. The changes produced by this and by the third wave, in the vicinity of the Bay of Corral, may be appreciated by comparison of the two maps, figures 33 and 34.

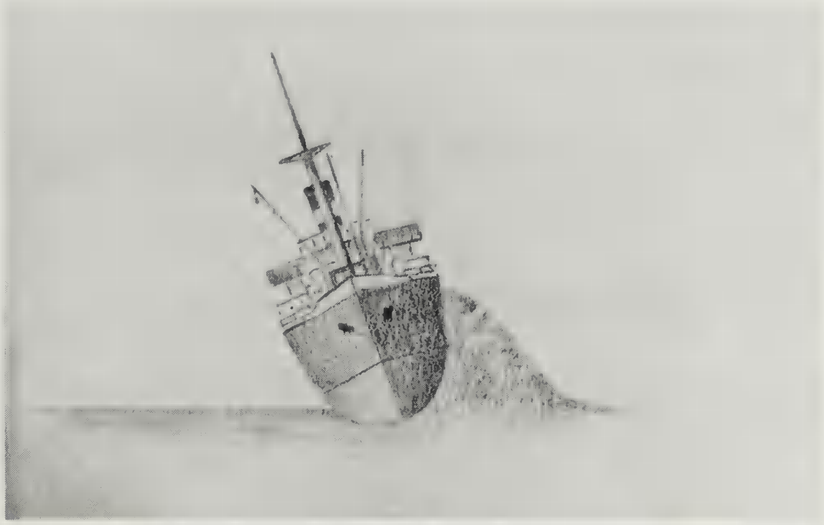
FIG. 32. Sand Accumulated on Starboard Side of the CARLOS HAVERBECK While She Was Aground on the Banco Tres Hermanas.

The third wave began to rise slowly, as the two others did, then sped up to 15 or 20 knots. The time this new wave began was not recorded, but its duration was estimated at 20 minutes. The water once again flooded a great zone, principally in Corral Bajo. It was observed to penetrate the farthest of the three, probably because the houses near the sea had been washed away and the water encountered less resistance in its advance. Some houses that had been washed toward the bay were returned and piled grotesquely against the hillsides (figures 35–38). This advance also capsized the tugboat ORIENTE which was thrown over the blast furnaces of Corral, where it remained on its side when matters returned to normal (figure 39). All but one crew member escaped with their lives.

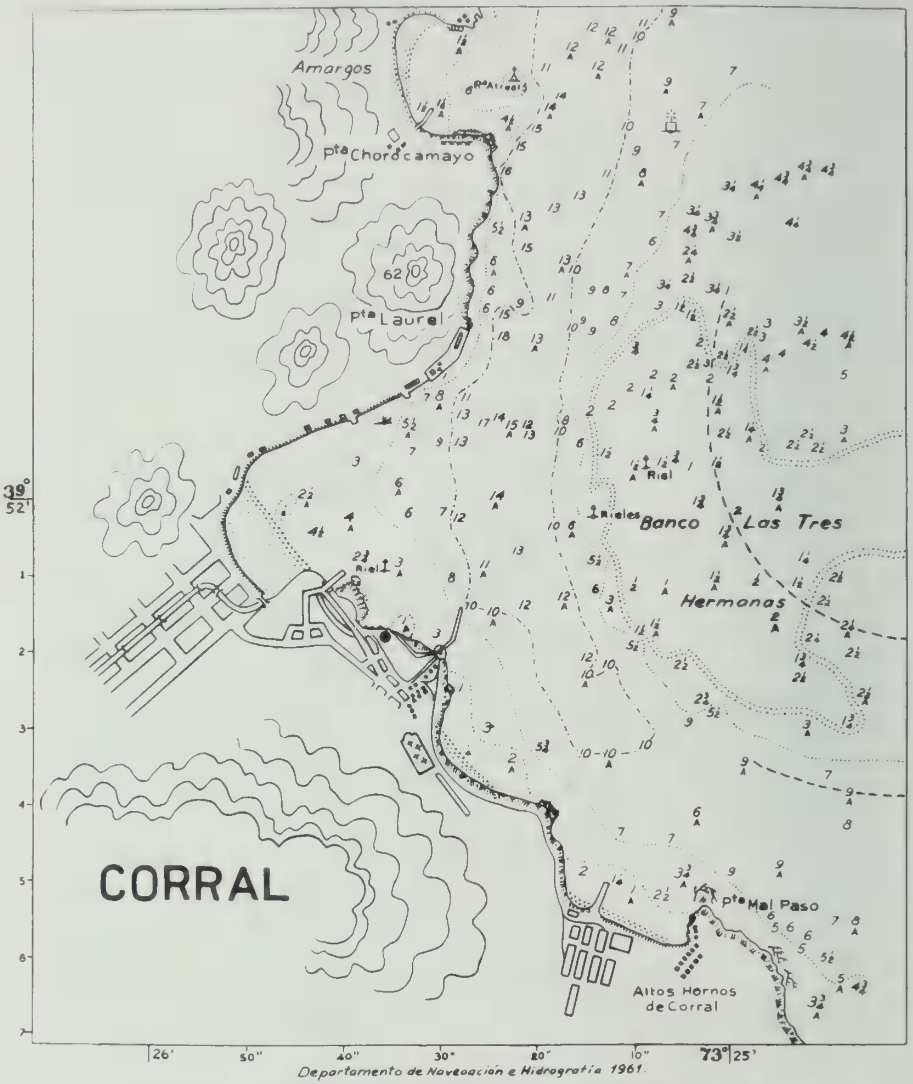

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FIG. 33. Details of Bathymetry in the Harbors at Corral before the Maremoto.

This was the last great wave. Many high waves continued for several days but were of gradually diminishing amplitude. When the water receded after the third wave there were no new phenomena noted in the Bay such as a recurrence of the trough at the side of Banco Tres Hermanas.

The destruction in Corral, as in the other ports of the Bay and the River, upstream as far as Valdivia, was extensive. The waves rose and fell along the River ravaging the low zones of Valdivia (figure 40). There are no data concerning the distance from the mouth of the River to which the effects of the tidal wave were felt, but this certainly must have been considerable.[3] The movement to which the ships anchored in the Bay of Corral at the time of the tidal wave were subjected, and also their tragic ends, merit meticulous description because they constitute a valuable experience and throw more light on the phenomena. Considering the complexity of

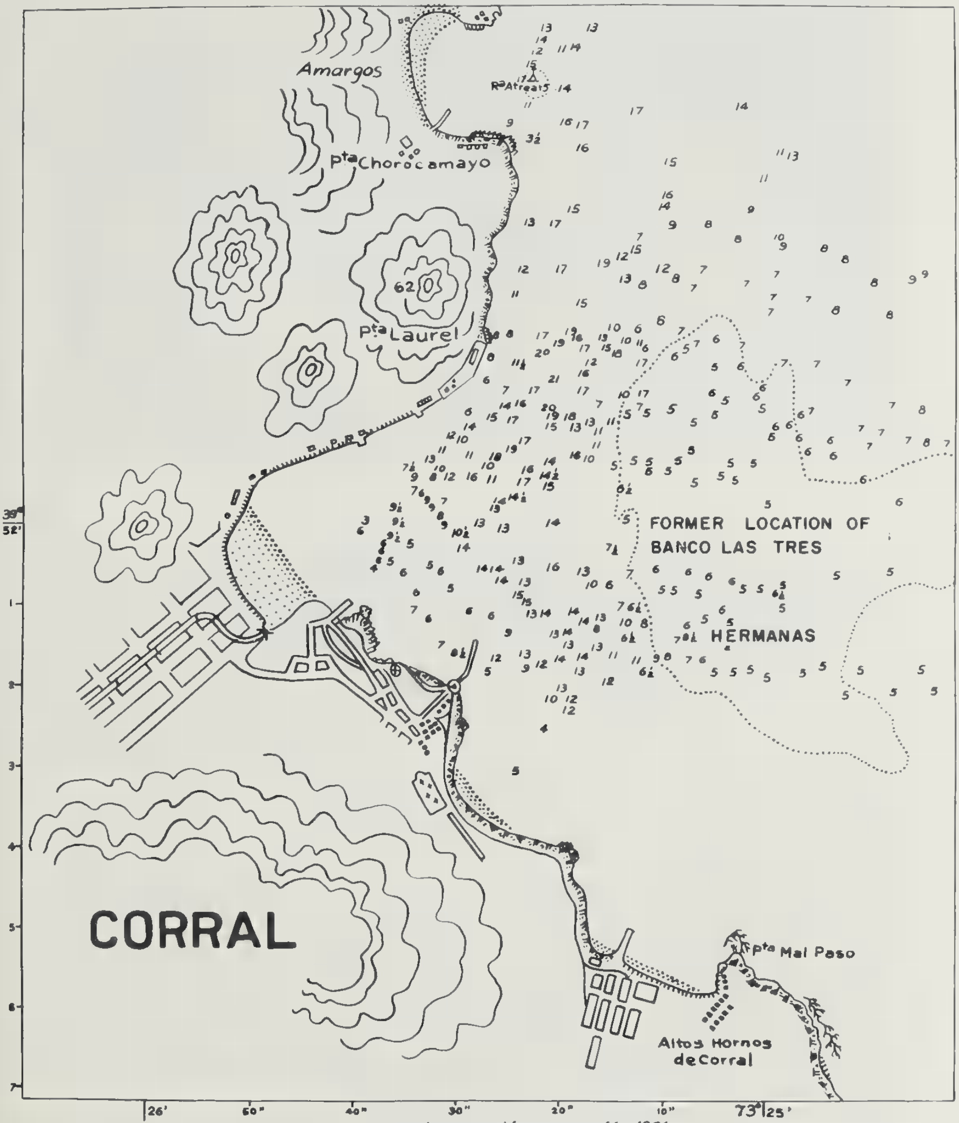

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FIG. 34. Details of Bathymetry in the Harbors at Corral After the Maremoto. Banco Tres Hermanas has practically disappeared.

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[3] Translator's note: Barges in the river at Valdivia were carried upstream and part of the airport was flooded.

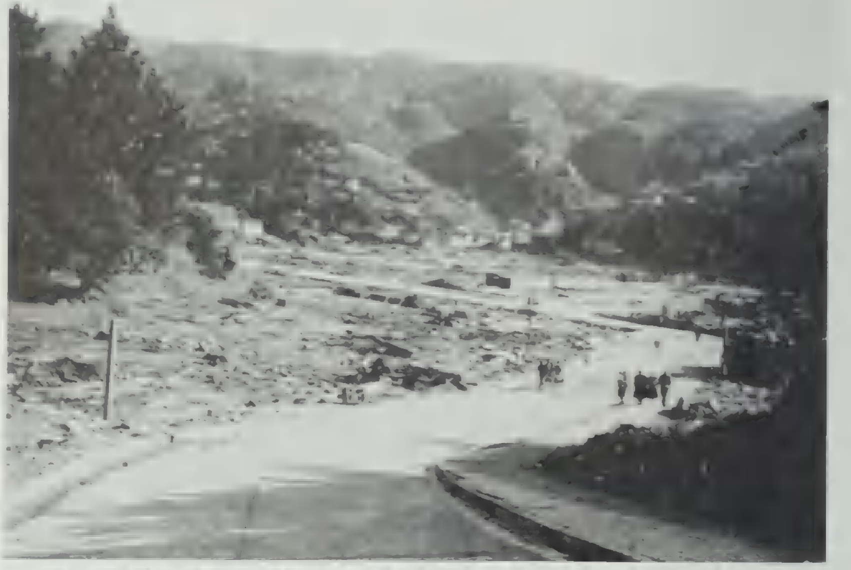

FIG. 35. Corral Bajo After the Tidal Wave (O. Arriagada photograph).

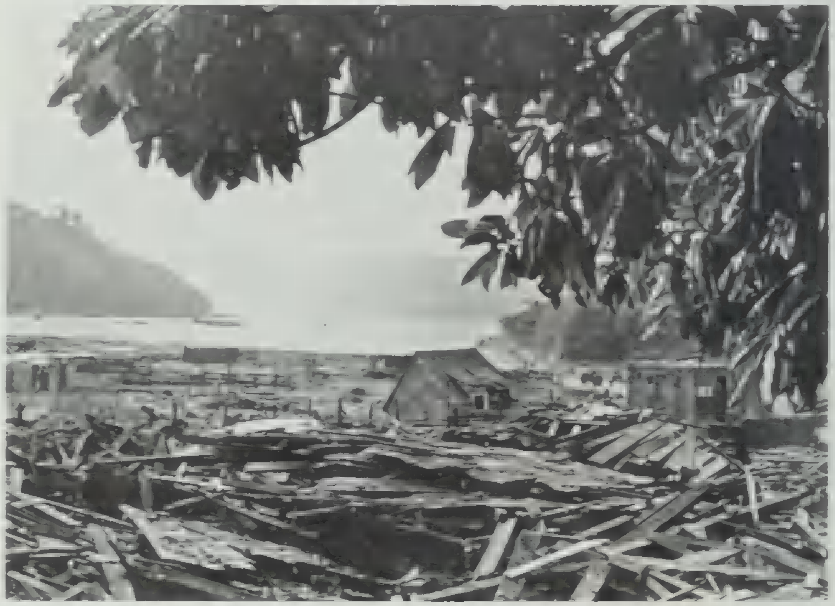

FIG. 36. Corral Bajo after the Tidal Wave, Seen from the Foot of the Hills Looking toward the Bay. The CARLOS HAVERBECK is visible in the water.

the situation, it has been deemed best to give a detailed description of events, treating each ship independently.

At the moment of the earthquake the boats were in the following positions: SANTIAGO (figure 25) was tied up at the muelle Frances (French dock) with two

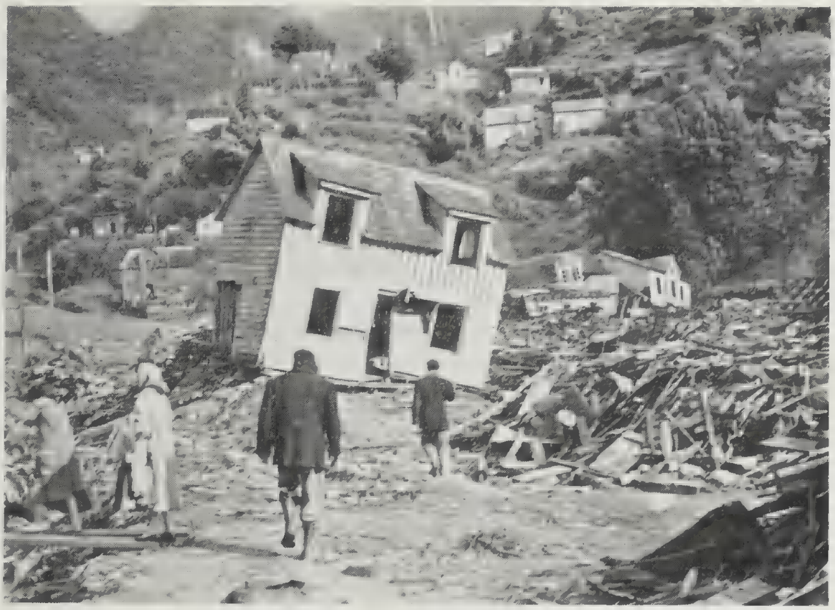

FIG. 37. Corral Bajo.

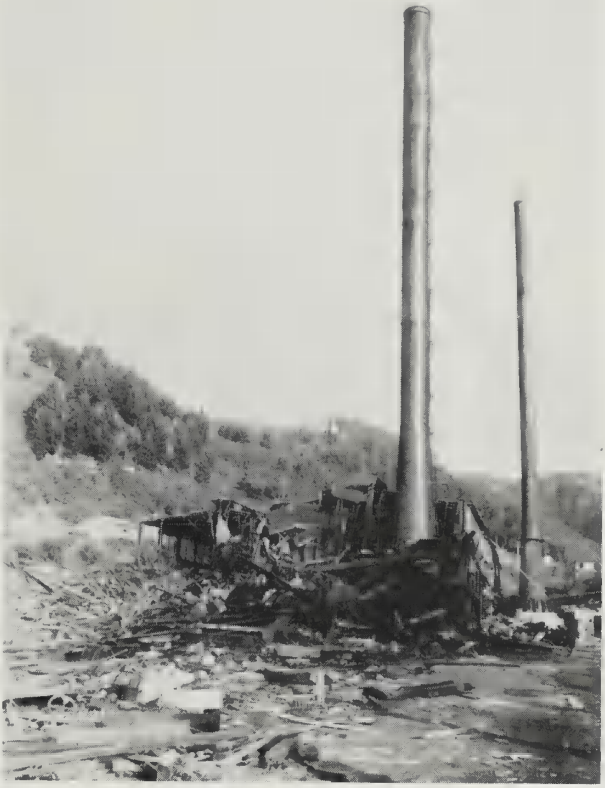

FIG. 38. Remains of the Whaling Plant in Caleta San Carlos (O. Arriagada photograph).

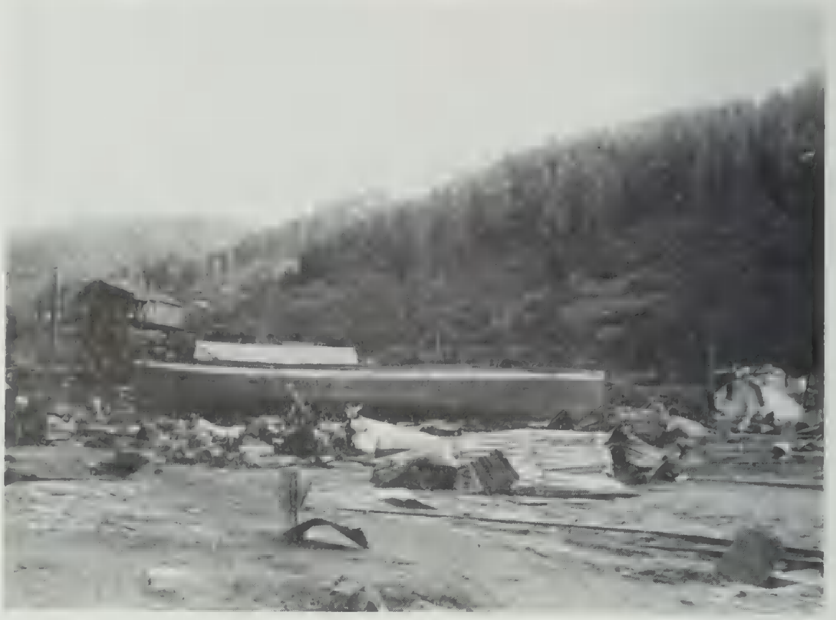

FIG. 39. Boat Thrown behind the Foundry by Tsunami.

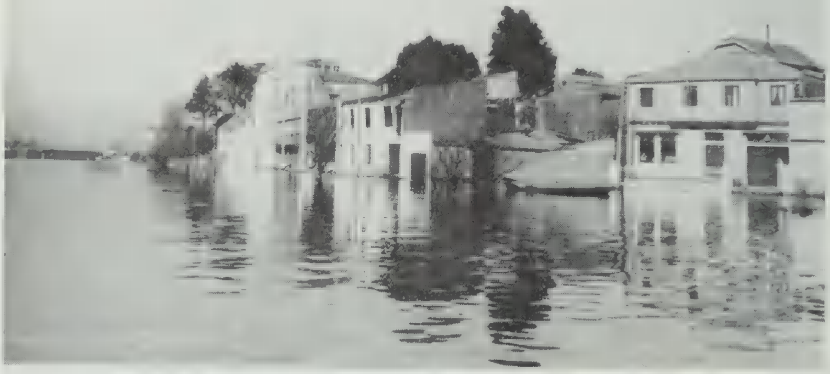

FIG. 40. Arturo Pratt Avenue Inundated by the Valdivia River (O. Arriagada photograph).

anchors set, two lines fast to a buoy at the port bow, two lines to the land by the stern, and a line to a buoy at the starboard stern.

The CANELOS (figure 41) was tied to a buoy with three 1-inch cables and an 8-inch line and was further held by two anchors, the starboard with 7 *paños*[4] of chain and the port with 5 *paños* of chain. The CARLOS HAVERBECK (figure 42) was anchored at the turn with two anchors, the starboard with 8 *paños* of chain and the port with 4 *paños* of chain, waiting for the tide so that she could fasten to a buoy, because she has just entered the port, at 1335 hours.

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[4] *Paño* is a Chilean measure of anchor chain. It is either 12 or 15 fathoms, usually 15; a fathom is 6 feet.

The first boat that suffered the effects of the tidal wave was the CARLOS HAVERBECK. When the wave appeared, it formed strong currents that began to drag the boat in the direction of Isla Mancera. As the current flow continually increased the crew let out 1.5 *paños* more chain. The motors ready from the instant the earthquake began, were set at full speed ahead. These measures, however, were not sufficient; the force of the current was too great. The capstans of the starboard anchor loosened, paying out the line, leaving the ship held by one anchor. The CARLOS HAVERBECK was dragged astern to position 3 (figure 42). A little later, the ship began drifting to port, toward the SANTIAGO, which was tied up at the French dock and trying to get loose. In spite of all the efforts to avoid collision, the CARLOS HAVERBECK scraped roughly against the side of the SANTIAGO. A small boat tied to the latter was totally destroyed, but served as a shock absorber in the collision. As the CARLOS HAVERBECK still had power, she arrived with the aid of her engines at position 5 in figure 42. There followed moments of currents and calms, which could not be detailed, that

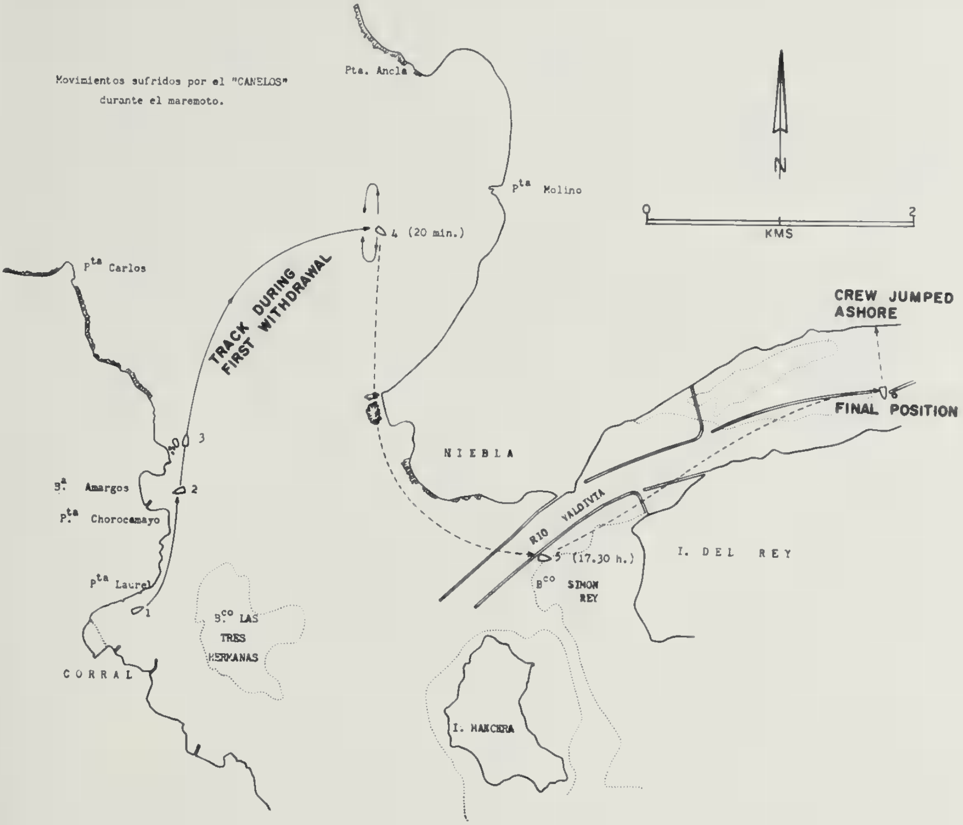

FIG. 41. The Career of the CANELOS.

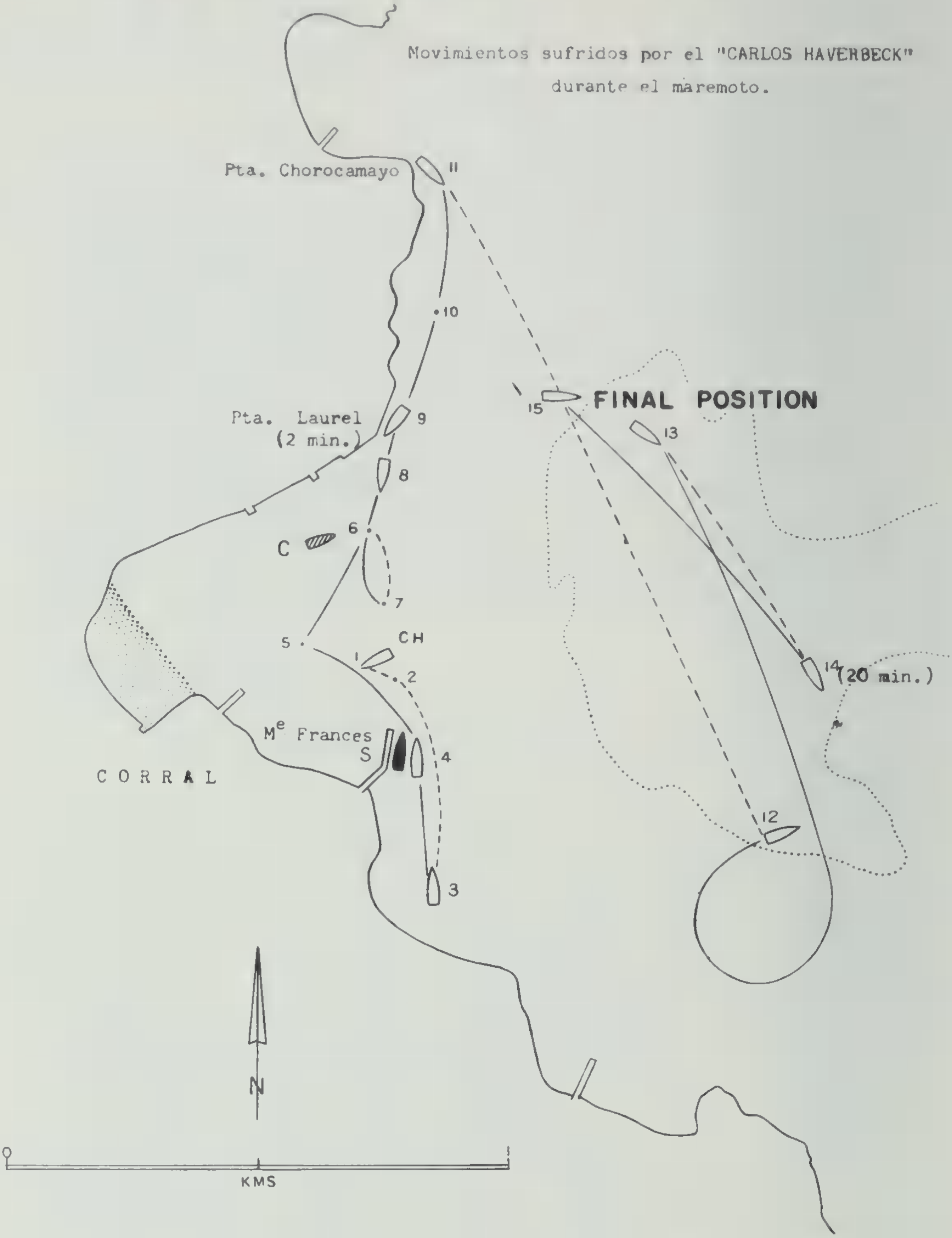

FIG. 42. The Movements of the CARLOS HAVERBECK During the Tsunami.

caused the ship to drift inside the Port. Suddenly, the CARLOS HAVERBECK was hurled over a buoy and, in spite of having stopped her engines, she tangled the cables of the buoy in her propeller and thus lost the use of her engines. While the ship remained between positions 6 and 7 it was noted that the French dock, to which the SANTIAGO was tied, fell over.

In taking advantage of a moment of relative calm, the CARLOS HAVERBECK tried to pass lines to the bows of the CANELOS which was at the time firmly maintaining her position. She called to the tug, PUMA, in the vicinity, which immediately responded, and requested her to carry the line to the CANELOS. The maneuver was about to begin when the first forceful withdrawal of the water took place. The CANELOS, because of the current, cut her cables and lines and at a velocity estimated at about 10 knots began moving seaward dragging her anchor chains. Following her, the CARLOS HAVERBECK was held by her port chain, about which she was turned, remaining with her bow in the direction of the Corral blast furnaces. As much chain as possible was paid out, but the brake of the capstan failed and the large chain ran out completely. At this point the CARLOS HAVERBECK was completely at the mercy of the tides and the current. The ship continued her vertiginous career toward the sea, passing very near the coast. Many houses were carried past her, some of which were between her and the coast. There was one moment in which the ship was stopped at Punta Laurel. It could not have been more than 2 minutes, but it was enough time for about eight stevedores to get ashore by jumping between the houses intercalated between the ship and the dry land. It was not possible for more men to do so because soon the boat was taken from this position and was run aground by the stern on Punta Chorocamayo.

The misfortunes suffered by the CARLOS HAVERBECK upon running aground were considerable. During the withdrawal, the ship remained aground at Punta Chorocamayo. Not knowing what might happen, the crew began efforts on board to put some escape cables to the shore, but, unfortunately, there was not time for this. They began to feel the effects of the second wave, which floated the ship again and carried her, half sunk by the stern, toward the Banco Tres Hermanas, where she ran aground in position 12 (figure 42). In this point she resisted the returning waters, which were described by the captain as a "very rapid tide without breakers that ran into the bay." All around the ship great whirlpools were formed. She remained in this position about 20 minutes.

During a moment of calm, while the ship was aground on the Banco Tres Hermanas, a dozen stevedores, without any orders whatsoever, left in one of the lifeboats, which was suspended from a single davit, and reached the land after considerable effort.

The other lifeboat was also launched carrying 22 persons but as soon as the boat had left the ship the current began running seaward. The boat returned to the side and the crew boarded the CARLOS HAVERBECK again, with the exception of three men: the third mate, a sailor, and a boatman. Of these, the last two disappeared and nothing more is known. The third mate, Sr. Eduardo Soto Ulloa, who was in charge of the embarkation, was miraculously saved. He told the following extraordinary history to his colleague, the first mate, Sr. Carlos Hartmann Orostegui.

No sooner was the lifeboat in the water than it was totally broken up by the strong current. The water had now receded sufficiently around the CARLOS HAVERBECK that one could walk on the bottom. He had hoped to get to the propeller and take hold of it in order to avoid being dragged away. He did not succeed in this objective because the current was too strong, but he saw that the blades of the propeller were doubled and the chain of the buoy still tangled in them. The outgoing current then carried him away toward the open sea. His memories are not very clear. He was struck several times in different parts of the body. The life preserver that he had put on saved him from being drowned. One time in the middle of the Bay he found a boat into which he climbed; a little while later the boat capsized and he fell into the water again. A strong current, probably the third wave, dragged him inland. He remembers that he succeeded in grabbing a spar and then lost consciousness. He came to at a place in Rio Valdivia called Cancahual, approximately 4 miles from the mouth, where he was rescued at about 2000 hours by the inhabitants. He suffered a fractured skull and one or two broken ribs. He remained in Cancahual from Sunday until Friday, when he was taken to Valdivia, there to receive his first medical attention since his adventure.

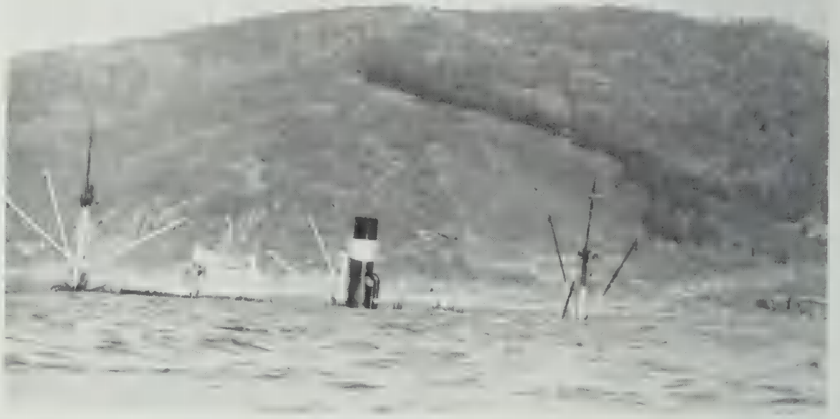

FIG. 43. The Steamer CARLOS HAVERBECK Sunk in the Port of Corral.

When the water withdrew after the second wave, the CARLOS HAVERBECK was grounded and then dragged to the north over Banco Tres Hermanas, running aground in position 13. From this point they were able to observe clearly the trough that formed and that the Bay was for a while practically dry. The current was very rapid and an accumulation of sand formed by the starboard side that contributed even more to the pronounced list of the ship (figure 32). The third wave dragged the ship, still over Banco Tres Hermanas, to position 14. While this was going on, the steamship SANTIAGO was seen going seaward on one side of the Bay; simultaneously on the other side, near Niebla, entering with great velocity and very steeply listed, the steamboat CANELOS was observed passing over the rocks and the breakwater that had been at the outlet of the Rio Valdivia. When the water went out this time the CARLOS HAVERBECK was dragged away once more, finally running permanently aground in position 15 (figure 42–44).

To the finish the saga of the CARLOS HAVERBECK, it is necessary to relate the salvation of the crew and officers. Even though there were no more gigantic waves, conditions in the Bay were far from normal. New waves swept the Bay, forming strong currents which made the disembarking enormously difficult. As the ship no longer had lifeboats it had to utilize its launch: under the command of the first mate, five successful voyages to land were made, transporting 10 to 12 crew members each time. The maneuver was difficult, long, and risky, but they were able to land all the crew (figure 45). At 2242 hours, when only the captain and seven officers remained aboard, the boat drew near the ship for its last load. A strong current developed that destroyed the boat against the side of the CARLOS HAVERBECK; the men in the little boat, however, succeeded in saving themselves. The list of the CARLOS HAVERBECK continued to increase until the water reached the boat deck. With great effort they succeeded in launching a raft and finally abandoned the ship at 2300 hours, at which time it had an approximate 60-degree list.

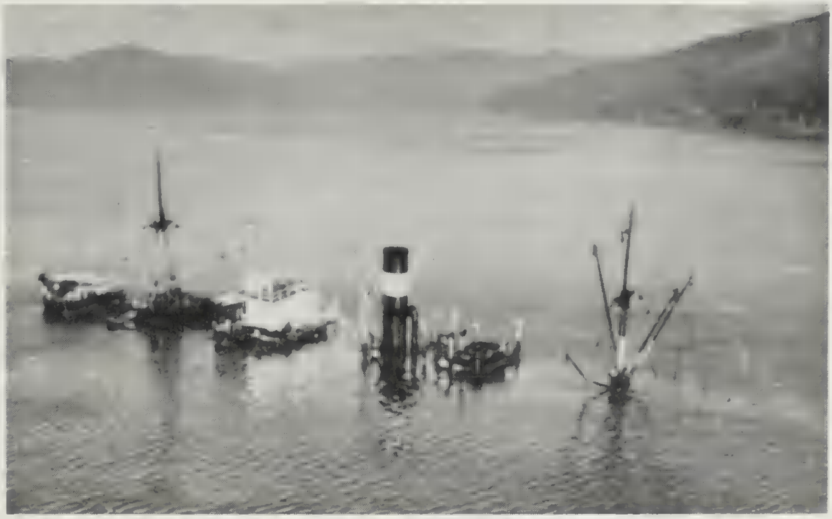

FIG. 44. Aerial View of the CARLOS HAVERBECK.

The raft was first swept to Isla Mancera (figure 46), but the men were not able to gain the coast of the island nor that of Corral. After that, the raft was washed, now toward the interior, then toward the open sea, until a stronger current carried them to the north. They passed within 200 meters of the SANTIAGO, which was now safe at anchor; they made luminous signals and shouted to her but the SANTIAGO was unable to give them aid. The current continued carrying them seaward until they were in front of Morro Gonzalo, where the current changed directions. Finally, they were left stranded on a beach to the south of Caleta San Carlos. Once ashore, around 0130 hours on 23 May, they climbed the cliff to a house where they spent the rest of the night. Near this house, on a plain about 25 meters above the level of the sea, they found the remains of houses and other objects that had been thrown to this height by the waves of the maremoto.

On their return by land to Corral, passing near Caleta Amargos, they saw in a canyon located behind a eucalyptus forest the mooring barge from Puerto Corral and the second story of a hotel from Amargos.

The other boat that was lost in the maremoto was, as has been said, the CANELOS, the property of the firm Haverbeck and Skalweit. The CANELOS survived the influx of the first wave, but when it receded the cables with which she was tied up to the buoy parted and she was carried outward, passing near the coast with anchors dragging (figure 41). When the earthquake occurred, the order was given to ready the motors, and the ship was thus able to help herself with them in the first phase. Another precaution that had been taken was to disembark all the stevedores as soon as the earthquake occurred. While in position 2 she was able, with the aid of her engines and anchors, to resist sufficiently well even though she lay athwart the advance of the waters and listed dangerously.

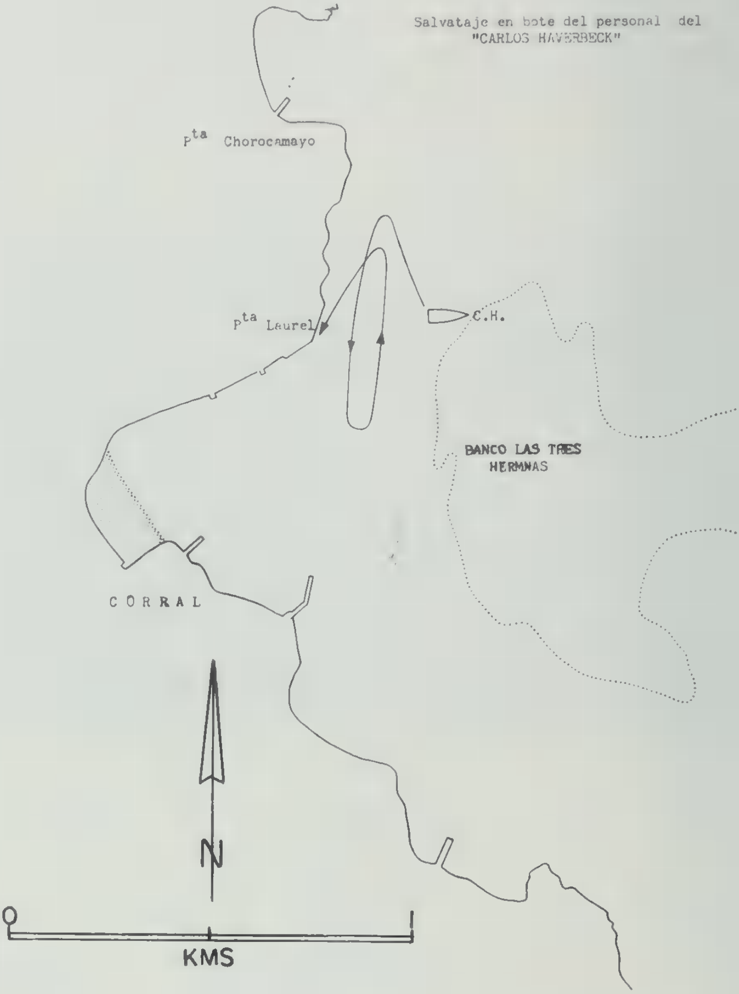

FIG. 45. The Course of the Lifeboat in Which the Crew of the CARLOS HAVERBECK Escaped.

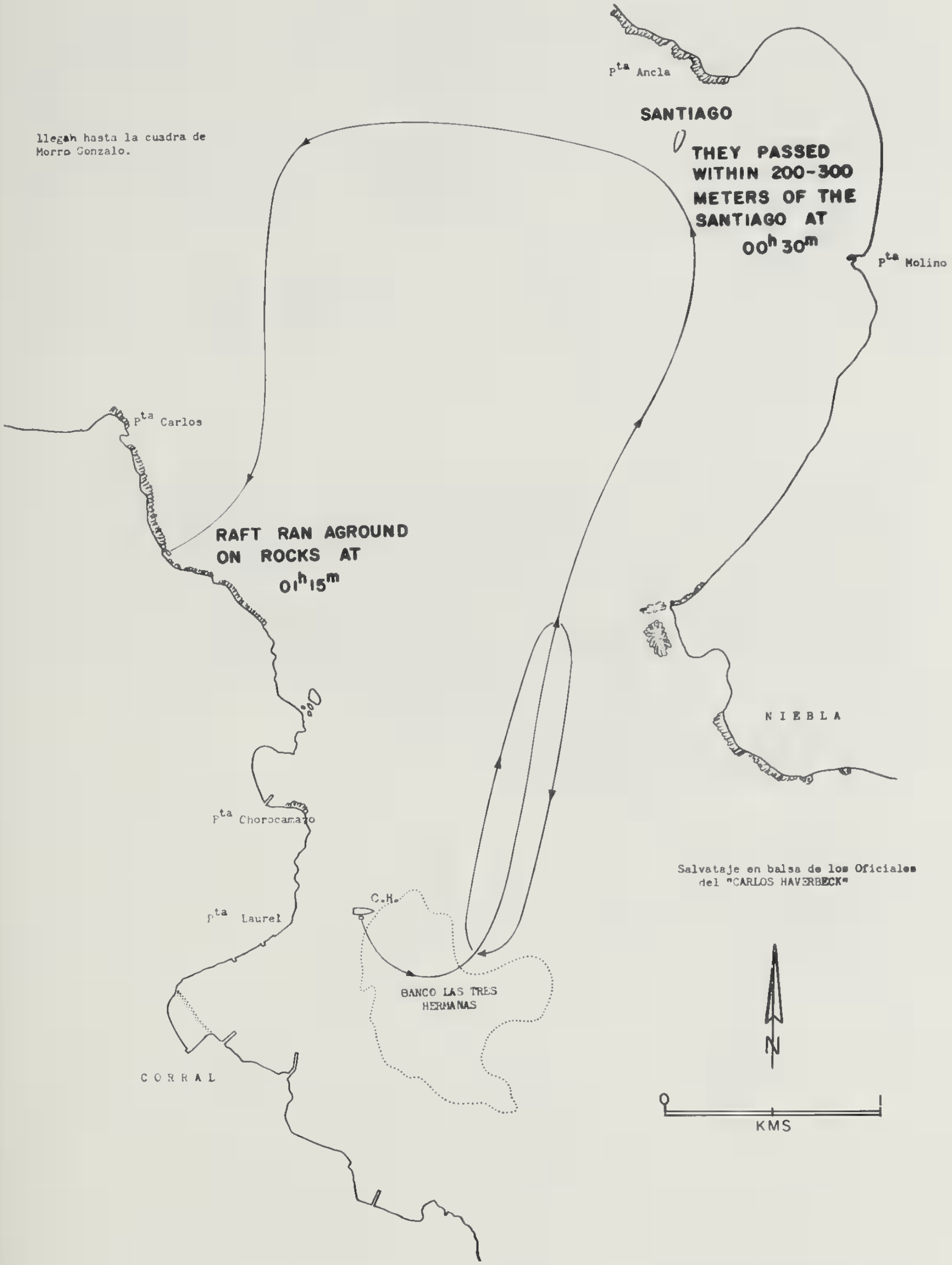

FIG. 46. The Course of the Raft on Which the Officers of the CARLOS HAVERBECK Escaped.

When the harbor began emptying rapidly, the boat was dragged to position 4. It has been calculated that it took only 10 minutes to run this distance of 1.5 miles. At this point many currents and waves were encountered that carried them now to the north, then more to the south. As the ship still had the use of her engines, the crew members hoped to be able to leave the Bay, so they began to weigh the anchors. While they were doing so, the outward current increased and the ship was left high and dry. The withdrawal was so rapid that they failed to stop the capstan and engines before they found themselves aground, so the propeller began to lift mud and sand from the bottom. This covered the intake of the condenser, leaving them momentarily without motors. From the CANELOS, it was seen that the anchor chains were stretched across the almost dry Bay of Corral. The center of the Bay now looked like a river whose water ran with great velocity seaward.

The pilot, Sr. Weller, said that at this time they looked toward the horizon and saw a wave whose height he estimated at 8 to 9 meters breaking and advancing with great velocity. Very soon this wave, the third, arrived at the ship carried her off listing more than 45 degrees. Part of the wave broke over the deck, leaving it full of sand, small stones, and fish. The wave washed the CANELOS away at about 20 knots toward the interior of the Bay and very near the coast of Niebla, with the bow toward the south. While the CANELOS was entering the Bay near Niebla, the SANTIAGO was leaving by the side of the Bay near Corral. The CANELOS passed, listing sharply, about 150 meters from the lighthouse at Niebla and was dragged over rocks that destroyed the keel. The crew saw that the boat was losing fuel. Shortly after arriving opposite the sea wall of Niebla, which had suffered grave damage from the first two waves, the ship turned (perhaps because the anchor that she was still dragging had caught and held for some minutes) and swung sidewise, grounding herself for 10 minutes on Banco Simón Rey, position 5 (figure 41). Here the crew noticed the currents that were running in Rio Valdivia: by the bank at Niebla, the water was lowering with great velocity, and a strong current was going up the opposite bank. It was this current that floated the CANELOS anew and carried her 1.5 miles upriver, finally leaving her permanently aground at position 6 (figure 47). The crew therefore abandoned the CANELOS at 1800 hours, because they feared she would overturn. The list was constantly being augmented by the accumulation of sediments along one side, and undermining of the river bed on the other side of the ship took place each time the current went out.

As has been mentioned, the steamship SANTIAGO was tied up at the French dock at the time of the earthquake (figure 48). A little while after the collision with the CARLOS HAVERBECK, the dock fell over and the lines were cut. The SANTIAGO floated off, passing over the fallen dock to position 2, where she withstood the first outflow with the aid of her anchors and motors. During the second wave, she managed to stay inside the port, although she was carried from position 2 to position 3, very near a tank constructed on some rocks in front of Sixth of May Street. From the ship it could be seen that a gigantic wave was inundating the Port of Corral and causing tremendous destruction there. The SANTIAGO became surrounded by the houses of Corral that were being carried away toward the open sea. Here the ship was passed very closely by the house of the Captain of the Port and the firehouse barracks, among others. The man in charge of the firehouse was ringing the bell. This man, when he realized that there was going to be a maremoto, climbed to the tower of the firehouse and, thinking it would be most effective to call the attention of the people with the bell, began ringing the bell loudly. He was doing this when the house was carried away by the water and, according to witnesses, continued ringing the bell even though he was in the middle of the Bay. Later this valiant *cuartelero* succeeded in getting to land, thus saving his life.

The SANTIAGO survived the third wave, but upon the withdrawal of the water following the third wave, she was dragged rapidly seaward with her bow to the south. The SANTIAGO left the Bay by a sort of canal that had been formed between the coast and Banco Tres Hermanas, at the same time that the CANELOS, on the other side of the Bay, was being carried upstream. Currents which had formed in the Bay dragged her from position 5 to 6, from where she soon drifted in the direction of Ensenada San Juan. With the withdrawal of the waters the ship was again swept seaward, her anchors dragging (they had not been cut loose, although the chains had been filed), to a spot in front of Ensenada Molino (position 9, figure 48). From the SANTIAGO some houses and, later, the raft with the officers of the CARLOS HAVERBECK were seen passing, but, because of the currents and waves, the SANTIAGO's crew were not able to help them. The SANTIAGO spent the night in this position. The next day they weighted anchor to search the zone in front of the harbor to see if the could rescue anyone. They then received instructions from the Dirección del Litoral to return to Valparaíso. However, although the SANTIAGO had succeeded in saving herself from the maremoto in Corral, she never arrived at Valparaíso. Instead she ran ashore on a point of Isla Mocha because abnormal currents caused by the tidal wave caused an error in navigation. Her radar had been inoperative and could not be repaired before the maremoto. The SANTIAGO was totally lost.

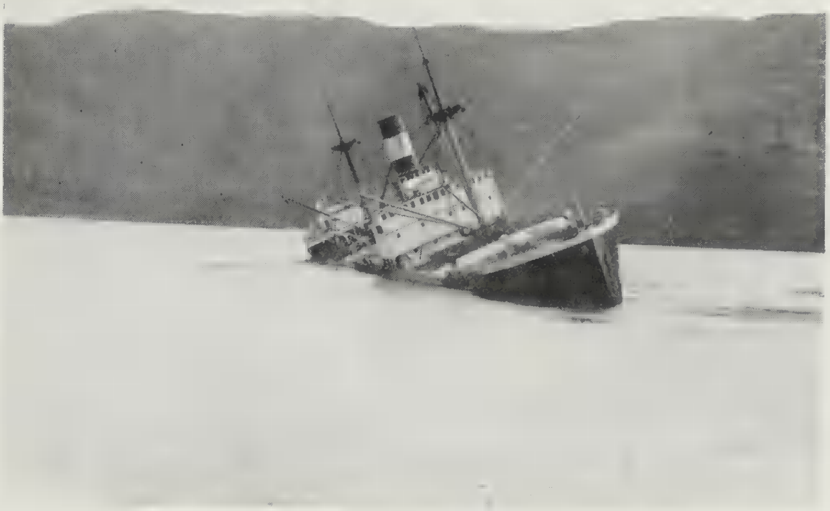

FIG. 47. The CANELOS Aground in the Valdivia River (O. Arriagada photograph).

The changes observed in the Bay of Corral and Rio Valdivia as a result of the earthquake and the tidal wave are extraordinary. It is sufficient to compare figure 33 to figure 34 to appreciate the changes in depth. In the rest of the Bay the changes

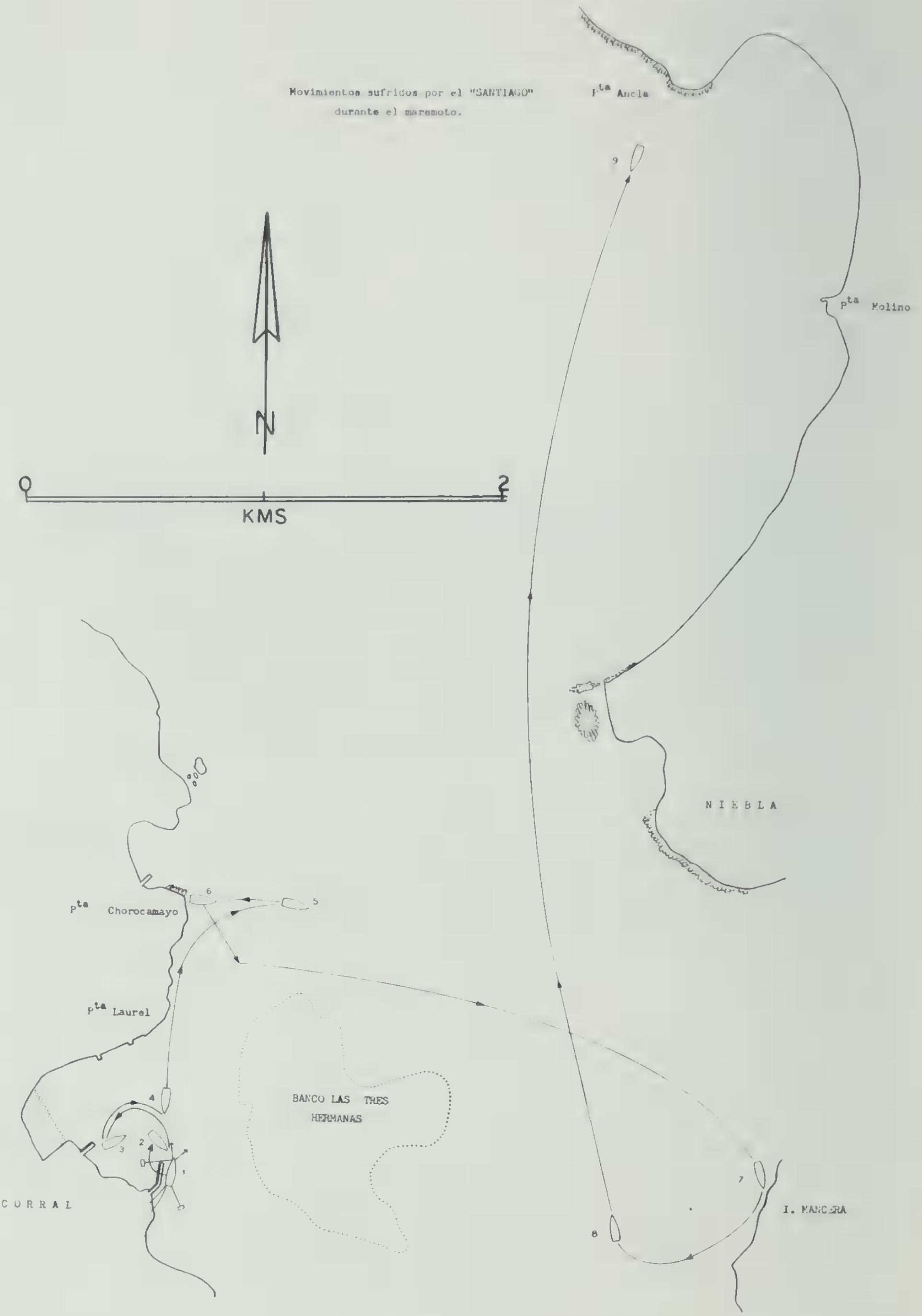

FIG. 48. Movement of the SANTIAGO During the Tsunami.

were similar. In front of the Bay, i.e., in the outer part, the phenomena are the opposite. There are zones in which the depth has diminished as much as 6 meters: for example, where the depth had been 32 meters it is now 26 meters. This is due to the fact that the waves swept the interior of the Bay and deposited the sediment on the exterior. When a complete new mapping of the Bay has been made it will be possible to calculate the amount of material transported.

Banco Tres Hermanas no longer exists. Over its former location there is now a sounding of 5 or more meters of water. In other places where there had been 2 to 3 meters before the tidal wave there is now 7 to 9 meters.

Rio Valdivia has also undergone increases in depth and is now navigable for boats of average tonnage. In addition to the increases in depth caused by the tidal wave, there was a sinking of the land estimated at 1.5 meters in Corral and Valdivia. As a consequence, Rio Valdivia was widened in the zones where its banks were low.

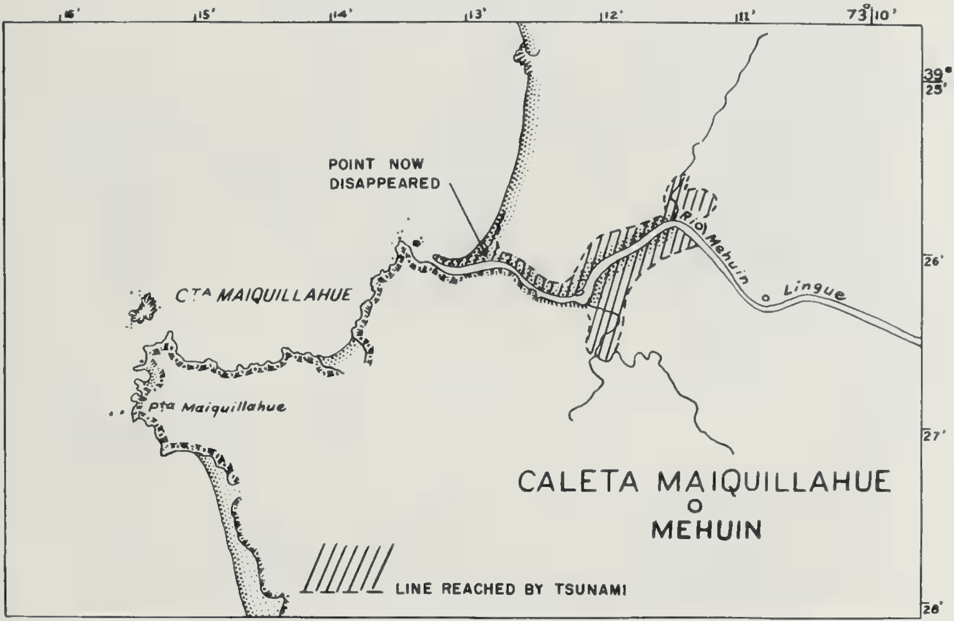

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Fig. 49. The Bay at Maiquillahue or Mehuin.

Mehuin: The first evidence of the tidal wave in Mehuin (figure 21 and 49) was a rapid withdrawal of the water from Rio Mehuin o Lingue. Fifteen or 20 minutes after the earthquake, a great, rapid increase in river level began. Then an enormous mass of water washed away the houses at the mouth of the river and began to wash away the first houses on the Bay shores. The formation of the waves, three in all, was observed to take place about 3000 meters from the coast. The highest wave was the third, estimated at 8.5 meters of height.

The Alcalde de Mar of Mehuin said in his report "Those of us who were on the south bank of Rio Lingue climbed the hills, from whence we observed the tragedy of the fishermen, who were fleeing through the brush with their women and children, falling and getting up again. Some of them were reached by the waves. Those who saved themselves took refuge on a little sand hill about a kilometer from the bay, others on a knoll at the mouth of the river, that subsequently remained isolated."

The building of the Marine Biology Station of the Universidad Austral de Valdivia was carried off by the first wave, washed seaward, and destroyed upon the cliffs of the coast.

As a consequence of the earthquake and the tidal wave there are notable changes in the river. A bar formerly made passage difficult for even the smallest boats, limiting usage to a maximum of 6 tons. Now the river can easily be crossed by large boats because the depth over the bar has increased. Furthermore, there was a straightening of the river, and several changes were made in its course. As in all the affected zone, a sinking of the terrane occurred, calculated to be about 1.5 meters (figure 50 and 51).

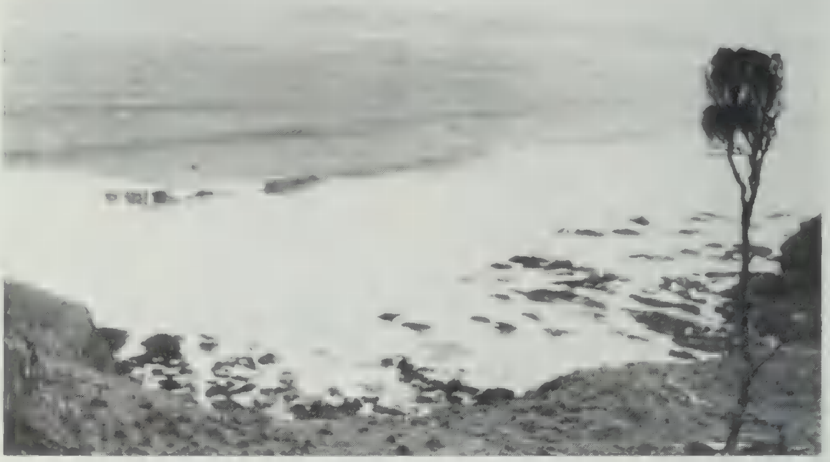

FIG. 50. Rocky Bay on the North of Playa Chica de Mehuin Before the Earthquake (W. Weischet photograph).

Queule: A little to the north of Mehuin is Caleta Queule (figure 21 and 52). No data have been obtained about the maremoto here, because the Alcalde de Mar of Queule died as a result of this phenomenon. The transformations suffered by the river were obtained through the kindness of the Alcalde de Mar of Mehuin, and the description of the consequences of the earthquake and tidal waves have been obtained from the work of Weischet (p. 19):

"Not a single house remained intact, and their remains are encountered as much as 2 kilometers toward the interior, together with the remains of fishing boats and uprooted trees disseminated in the muddy forest or over a meadow at the foot of the coastal cordillera. The breaker that passed over the village reached a height 4 meters on its arrival at the first houses, mute witnesses of this fact are the pieces of

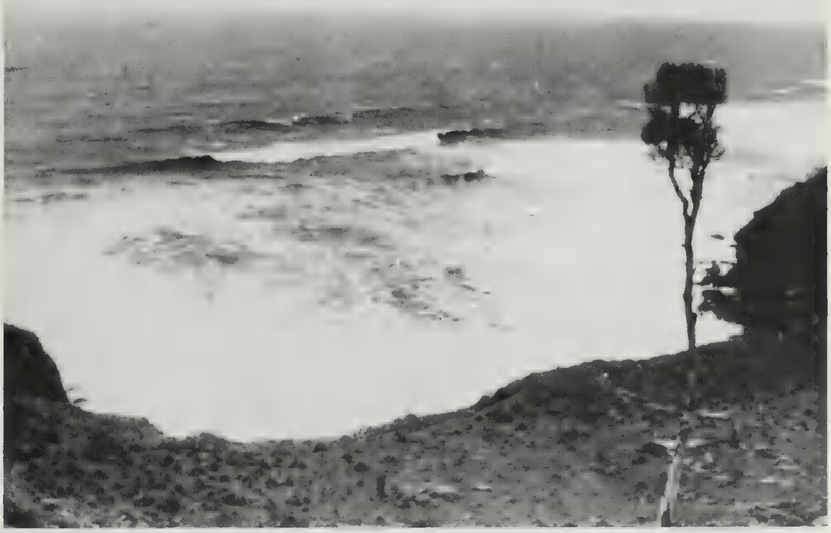

FIG. 51. The Same Bay as in figure 50, after the earthquake. The abrasion platform is permanently submerged (W. Weischet photograph).

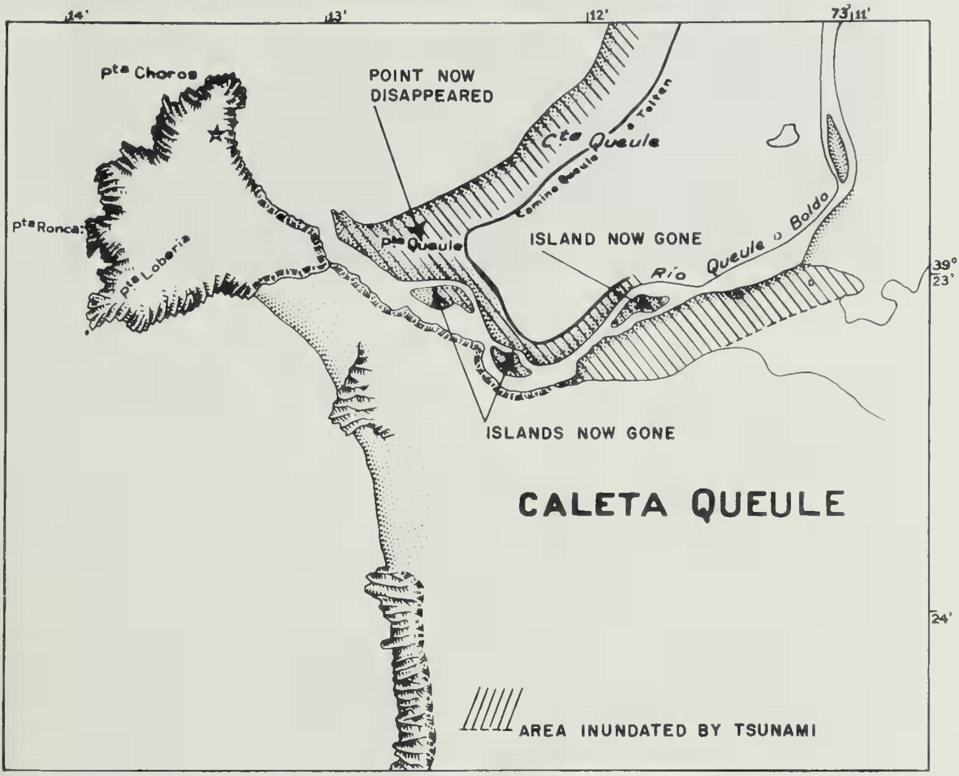

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FIG. 52. The Bay at Queule.

floating wood that have remained entangled in a group of trees. These trees supporting one another were not doubled by the waves. It is accurate to consider that the great wave had passed over the shore ridge and had travelled, before arriving at the houses, a distance of 1.5 kilometers toward the interior."

"The river augmented its width, the inter tidal zone reached to the western bank of the old village and the work of the tides has converted the estero, formerly a meander, into a small estuary" (figure 53–56). The bay also suffered some changes which were described as follows: "The bar of the Caleta [bay] was opened into a canal 5 meters deep bordering the coast. The former bank of the mouth of the Rio Queule has disappeared."

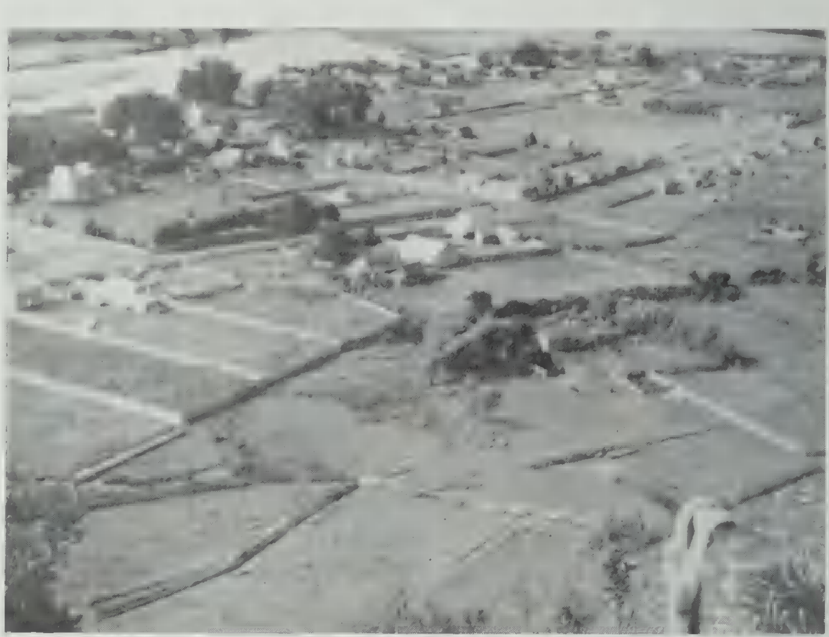

FIG. 53. Village of Queule Before the Catastrophe (W. Weischet photograph).

Puerto Saavedra: The most noteworthy physiographic feature of the Puerto Saavedra area (figure 21 and 57) is the offshore sand bar that encases a large stretch of the Rio Imperial and separates it from the sea next to the coastline. The earthquake did not produce much damage in Puerto Saavedra, but the tidal wave destroyed it almost completely.

The first evidence of the tidal wave was a great withdrawal of the waters that augmented the current of the river, 25 to 30 minutes after the earthquake. A little later the first wave, 3 or 4 meters in height, reached the coast and carried away part of the offshore bar. The third wave was the biggest of all; its height has been calculated at 7 to 8 meters. It totally destroyed the village. It penetrated to the interior as far as the mouth of the Rio Imperial and opened a new mouth across the offshore bar. According to information received, several other high waves came during the night. One inhabitant of Puerto Saavedra, whose house had been protected by a pine forest, spent the night on the roof while the zone around him was inundated repeatedly. The remains of many houses were encountered 2 and 3 kilometers inland. A newspaperman described what he saw in Puerto Saavedra as follows: "Now the only indications of its extinguished existence are some roofs upon the soil and hundreds of tablets that served as the walls of the fragile houses of the villagers. Only the cracked walls of the church and the principal buildings that surround it remain standing, along with the local school.

"The tiny settlement, Nehuenté, situated on the other side of the Rio Imperial, disappeared completely. There is not remaining a single wall to indicate its existence.

"Trovelhué, at more or less 40 kilometers, was submerged in the river water, but upon the retiring of the water its inhabitants returned to their houses.

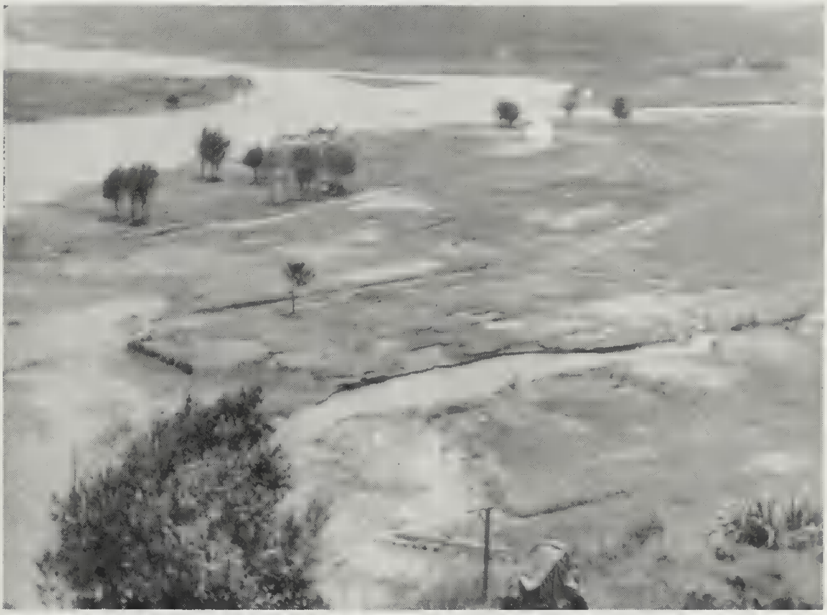

FIG. 54. The Same Region as in figure 53 (the Trees Serve to Identify Locations). The village was destroyed by the second wave. The sinking of the continent produced a transgression of the sea into the western part of the village site (W. Weischet photograph).

"Between Trovelhué and Puerto Saavedra the landscape is completely altered because the river changed its course, carrying away a great amount of beach and terra firma."

Among the houses still standing, mentioned by the newspaperman, one house in Puerto Saavedra that was not destroyed should be pointed out. It belongs to Sr. Pablo Lüer and is north of the village near the mouth of the Rio Imperial. The report of Watanabe and Karzulovic (p. 49) says in this respect: "This is in a higher terrain than the rest of the town and has a bunch of trees between it and the banks of Rio Imperial. It is evident that this row of trees, even though it is very small, diminished in notable form the force of the tidal wave, protecting the houses from certain destruction. In this same house the sea reached an altitude of about 60 centimeters over the foundations. In the other houses the sea rose to a level of several meters."

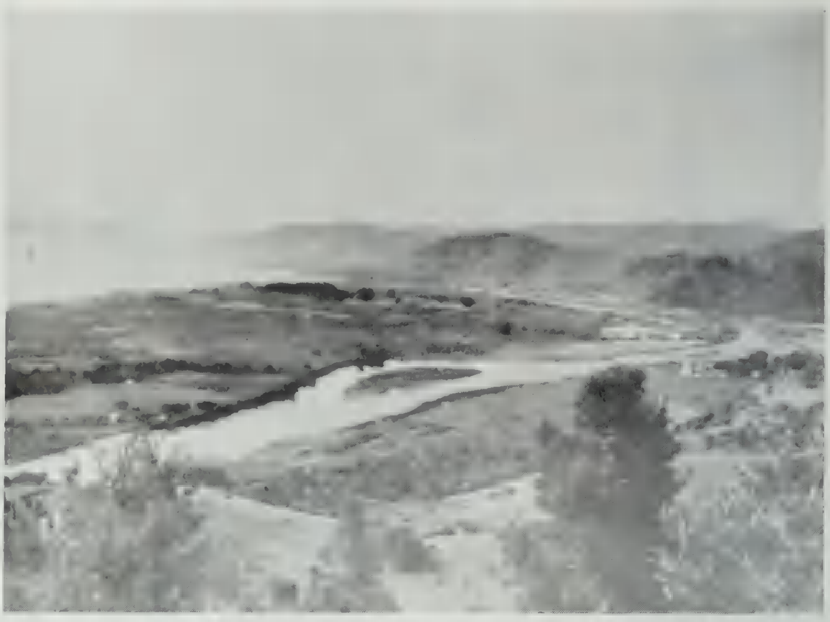

Fig. 55. View of the General Region of Queule before the Earthquake. The village is in the extreme right (W. Weischet photograph).

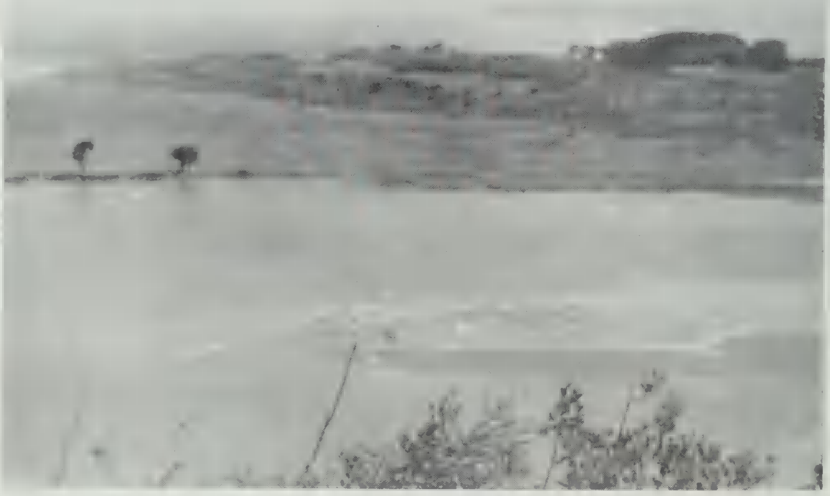

Fig. 56. This View Takes in the Lower Left Part of figure 55. The river has widened and the coastal area is swept clean.

According to Weischet, the Rio Imperial now empties through the mouth opened across the offshore bar. The width of the mouth is now about 1,000 meters. "The rest of the littoral barrier is now an island, which in its extreme north doubles against the south bank of the Imperial River. It now seems that Puerto Saavedra is separated from the river and its actual location is on the side of a lagoon that has a very narrow and shallow exit. If this situation continues, the entrance to the bay will be filled by beach sediments and this ancient port will be separated from the sea."

The new mouth of Rio Imperial was investigated by the Navy corvette Casma and described as follows:

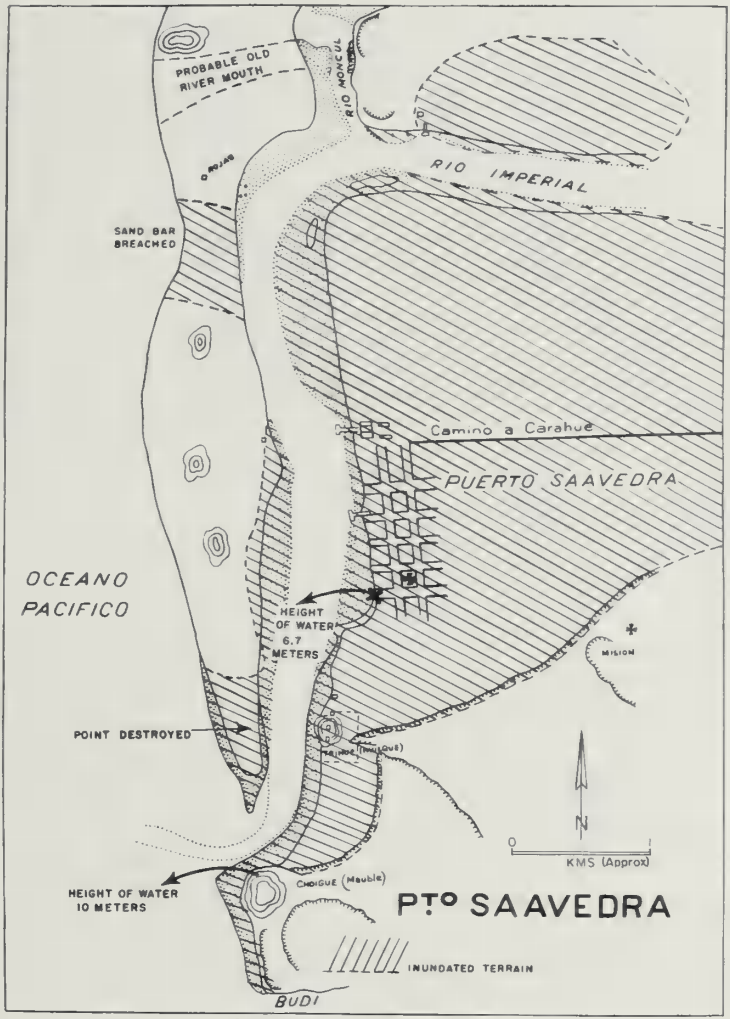

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FIG. 57. Puerto Saavedra.

"The coast in front of Rio Imperial from Morro Cautén to the south of the old mouth from about a mile of the coast was investigated; it was obviously unapproachable over its whole length, with strong breakers that impeded the approach of any small boat. Great landslides were seen in the hills from Cautén southward, with slides that practically divided the hills in two and at times with tremendous fractures oriented north-south.

"As a consequence of the earthquakes and tsunamis, the sand bar that exists between the conjunction of Rio Macúl and Rio Imperial toward the south has been opened for a thousand meters.

"The offshore bar, or littoral ridge, referred to before is a tongue of earth and dune sand some 500 meters in width and 10 to 15 meters high. Before the earthquake, in the place at which the bar was broken, Rio Imperial overflowed to the sea in winter by a tiny riverlet.

"The mouth now presents steep banks of sand and earth about 10 meters high, and breakers 3 to 5 meters high now totally occlude the entrance. The conditions that they could observe in the new mouth were completely adverse to the use of a small boat."

As in all the affected zone, Puerto Saavedra suffered a general sinking of 1.2 meters.

Isla Mocha: On Isla Mocha (fig. 21 and 58) the earthquake was felt with great intensity and great landslides occurred that swept away everything in their paths, such as trees, animals, etc.

At some places, cracks were produced in the ground.

The sea wave began about 10 minutes after the earthquake, the first evidence being a withdrawal of the water from 100 to 200 meters. Then came three waves that approached the island from the southwest, affecting the south and west coasts with greatest intensity.

The first wave was highest and reached an estimated height of 15 meters. The houses of the inhabitants, as well as the buildings of the lighthouse, dock, etc., located in Caleta la Hacienda, were totally erased.

The island and adjacent zones were uplifted an estimated 1.7 meters. This may be demonstrated by rocks that now crop out of the sea, as well as by soundings made inside the 10-meter level, by which it was proved that they are now 2 meters less.

Lebu: The phenomena in the port of Lebu (fig. 21 and 59) were completely different from those in the zones farther south. In this port, the most important seismic movement was that of 21 May at 0605 hours. During this earthquake, the land was uplifted about 1 meter. According to the Captain of the Port the following evidence exists:

1. An uplifting of the river bed and adjoining banks was noted. The river was left without flow except in the middle, while the banks and docks remain dry at low tide and with a depth of only about 1 meter at high tide. This makes navigation by tugboats and cargo barges in Rio Lebu quite impossible.

2. The bar at the river mouth was displaced by an uplift of the land that formed new embankments of sand and sediments that have made navigation of tugs with drafts in excess of 1 meter even more difficult at low tide.

3. Coal may be loaded from the Errázuriz dock of the Victoria Coal Company only at high tide.

4. Rocks that surround the shallow places in the port are now exposed to view.

5. El Guape, a stony island that serves to break the ground swell, formerly disappeared during high tide. Now it is seen as a pinnacle that the high tide covers only by half.

The tidal wave of 22 May affected the port of Lebu but elapsed time between the

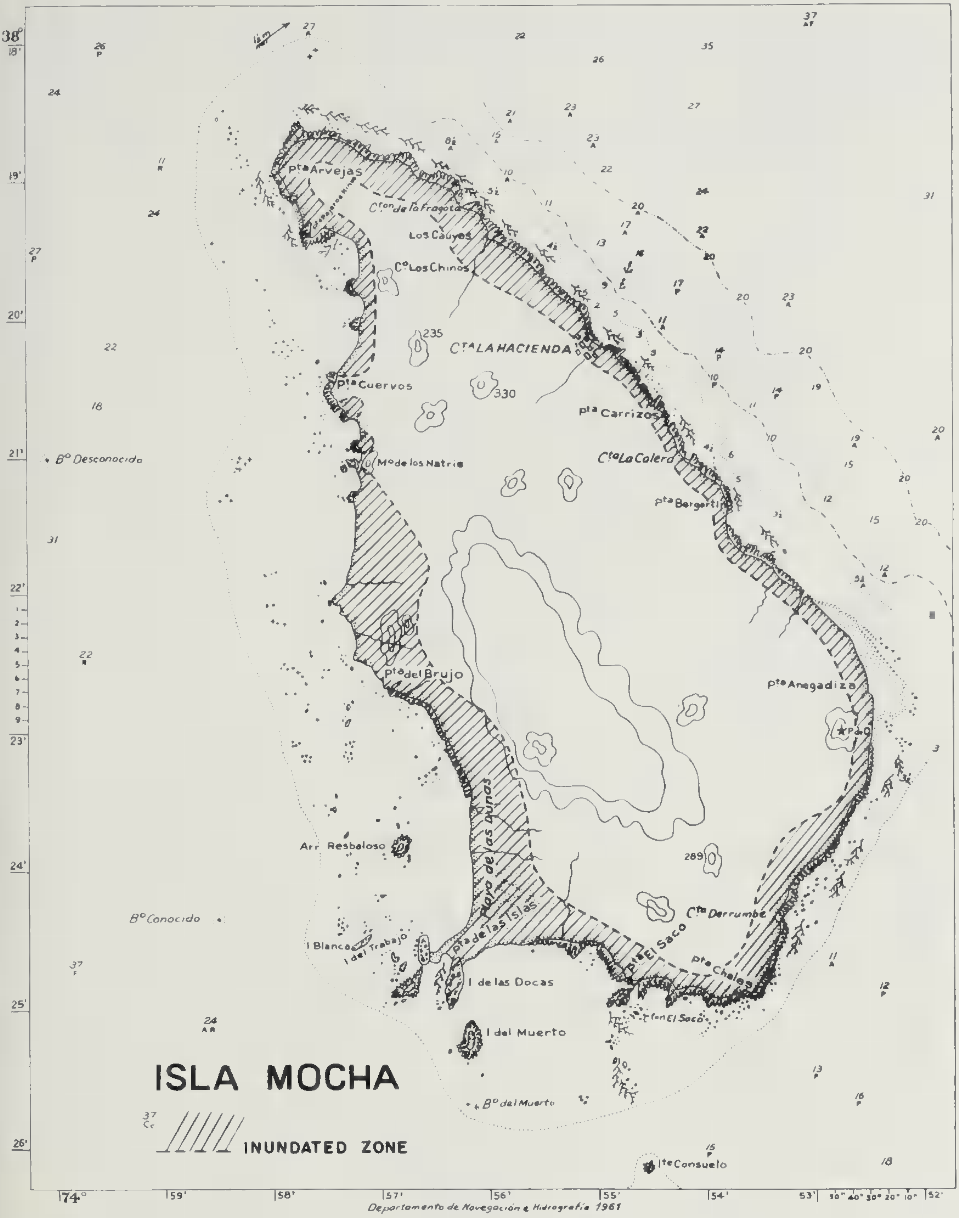

FIG. 58. Isla Mocha.

earthquake and the maremoto was not recorded. Three waves arrived at the coast whose maximum heights were estimated at 3 to 4 meters. The waves were felt as far as 5 km up the river.

Lota: The Captain of the Port of Lota (fig. 21 and 60), with the pilot of Lota, observed the phenomena that affected this port from the Fiscal dock.

First, strong breakers formed at Punta Escoria. At 1600 hours the sea withdrew about 150 meters horizontally. A little later the first wave arrived. This reached points about 20 meters farther inland than the tides of the syzygies. This phenomenon was repeated five times, the last advance being at 0200 hours on 23 May. The abnormality of wave conditions continued decreasing until 27 May.

The vertical height of the waves was 1.5 meters over the average level of the sea.

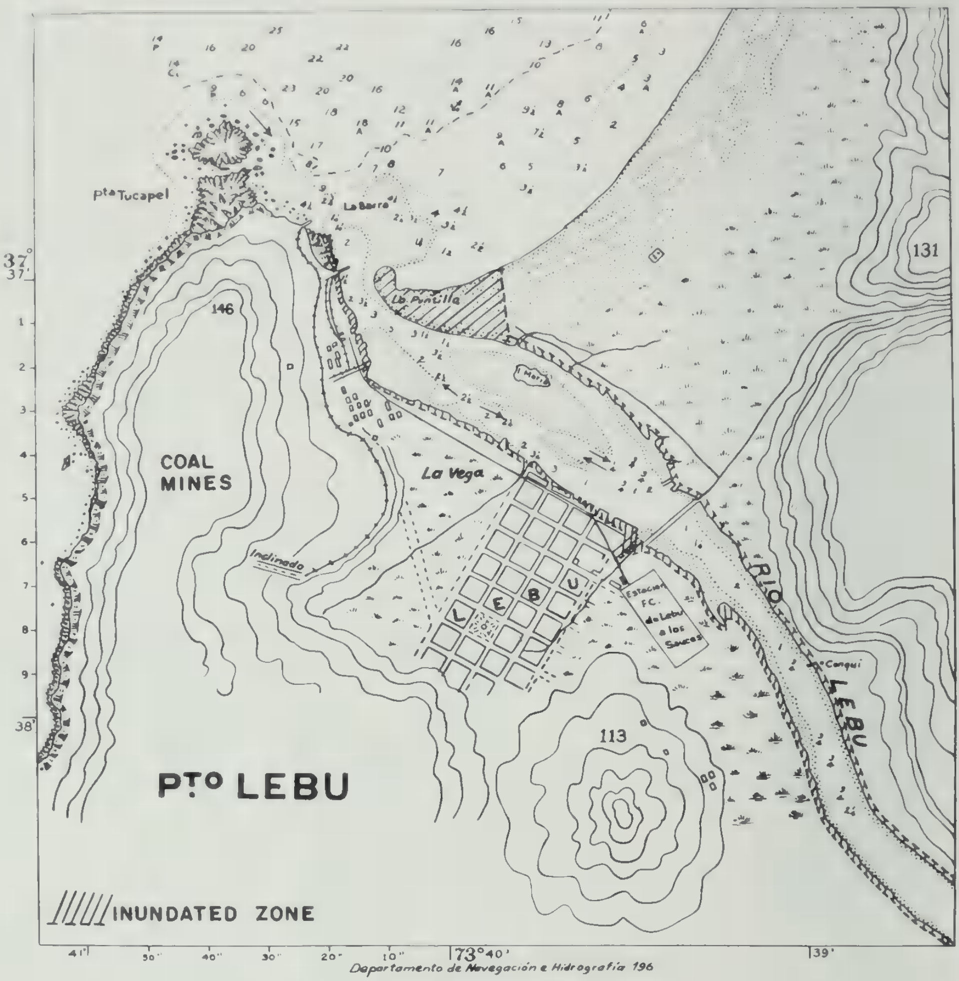

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FIG. 59. Lebu Harbor.

Isla Juan Fernandez: The first alterations of the sea in Bahia Cumberland (fig. 61, Isla Más a Tierra of the Archipelago of Juan Fernandez) occurred while the majority of the inhabitants were on the dock or nearby, observing the arrival of the sailboat ROBINSON CRUSOE that was coming from Valparaíso.

The sea slowly withdrew about 30 meters horizontally, producing great consternation among those present. Precautions were immediately taken to save the smaller ships at their moorings. Six to eight waves followed whose altitudes were not estimated[5] but which caused no damage except to carry away some boats that were later retrieved.

There is no information as to what happened on the other side of the island because that coast is completely uninhabited and very difficult to reach. The coast was certainly affected because it lay athwart the advance of the waves.

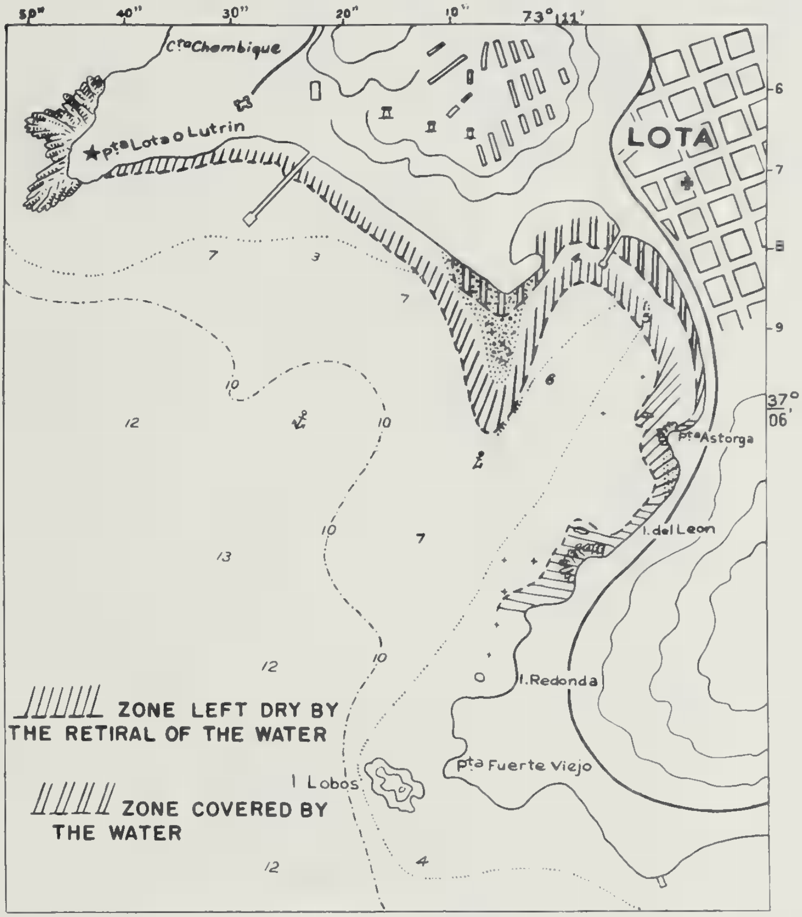

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FIG. 60. Lota Harbor.

Isla de Pascua (Easter Island): The population of Isla de Pascua (fig. 62) is concentrated at Hanga Roa, on the west side of the island, hence there were no witnesses to the maremoto, which affected only the coast that faces the South American continent. The Military Chief of the Island estimated the height of the waves at about 6 meters. There is evidence that the sea penetrated the lower parts of the islands to 500 meters, probably aided by a strong wind that was blowing that day.

In addition to destroying some windmills used to pump water for animals and some stone fences, it destroyed the Ahu of Tongariki. Ahus are platforms of stone upon which in the past the islanders erected statues of stone, which later were thrown down, remaining in the near vicinity.

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[5] Translator's note: The height was estimated by the translator at 1.5 meters.

The Rev. Padre Sebastian Englert, who visited the site, described what he saw as follows (Englert, 1961): "I saw with surprise what may be described only by the graphical expression that 'no stone remained upon stone'! An enormous avalanche of water, probably reaching some 6 meters over the level of the sea, invaded the coast of Hotuiti for a distance of 500 meters and swept away the ahu, statues, sunshades, fences, and blocks of stone with such force that only a person who had known the ahu well before its disappearance could now establish its former location.

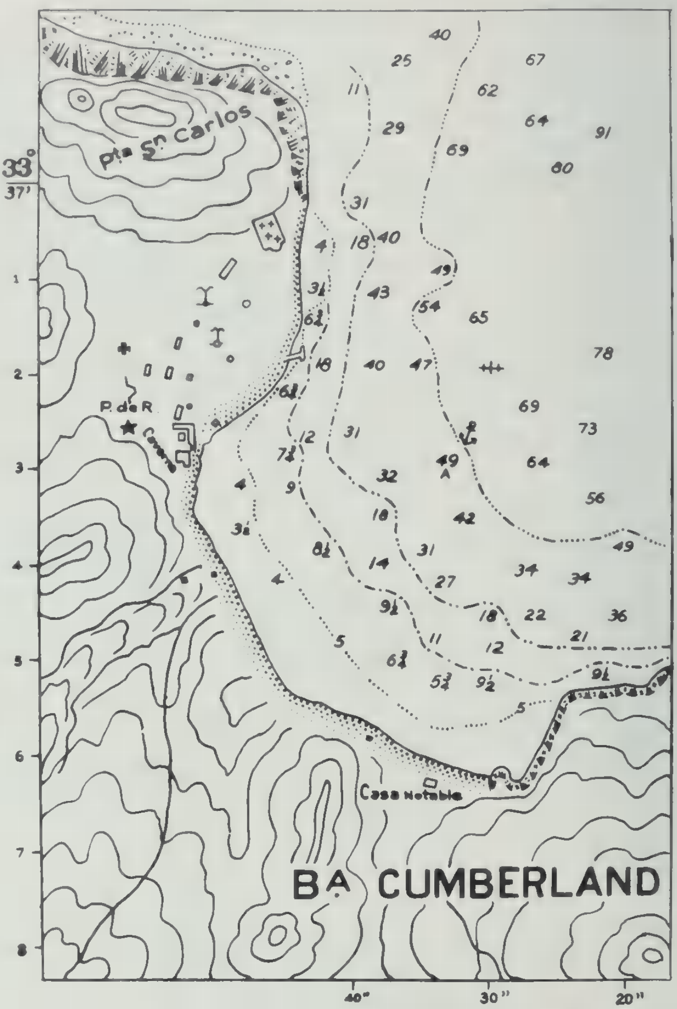

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FIG. 61. Cumberland Bay; Juan Fernandez Isla Más a Tierra.

"The waves of the sea appear to have played with the heavy statues as if they were balls. They remain scattered around 50 to 150 meters from the site of the ancient ahu. I was especially taken by one of these and was struck by its beauty. Even though, some years before, it fell my lot to inventory all the statues of the island and to put numbers on them, I had not appreciated the state of sculptural perfection because the head and chest had been partly buried. Now it lay stretched out mouth upward among stones and rubble some 100 meters from its former location. As it measured 6 meters in length by 3 meters in width at the widest part of the trunk, from arm to arm, it was possible to calculate that it weighs at least 20 metric tons. The waves of the sea transported it with an irresistible, but at the same time such gentle, force that it had not deteriorated nor fractured, and the perfect form of the face and chest causes admiration."

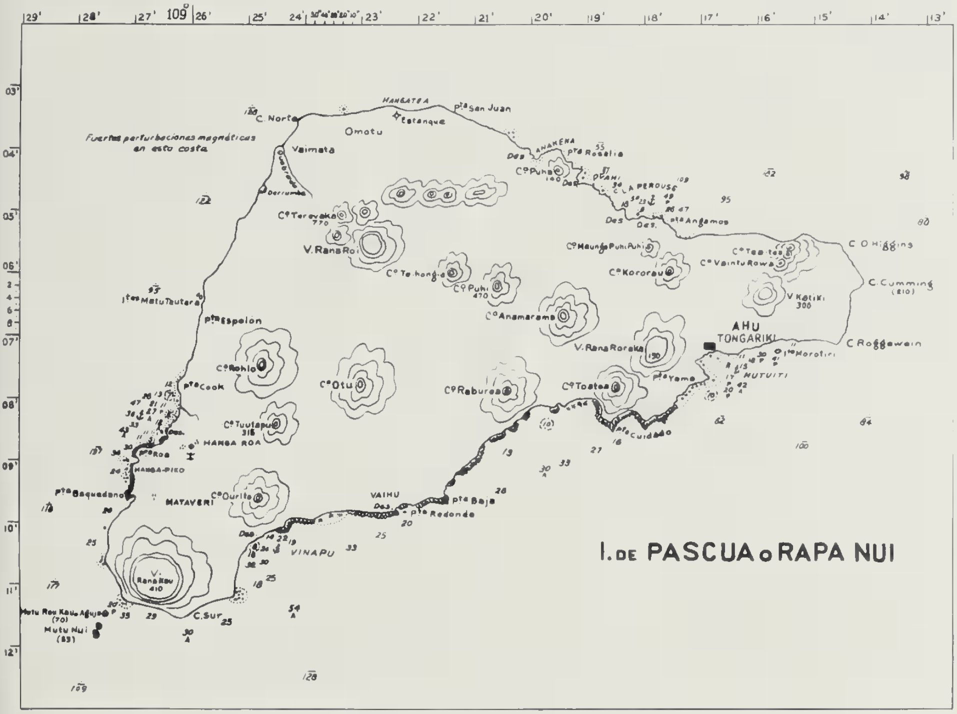

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FIG. 62. Easter Island, Showing Ahu of Tongariki.

PART III. PORTS OF TALCAHUANO AND POINTS NORTH

From Talcahuano to the north, records of tide gages are available from which the exact times, amplitudes, durations, and forms of the waves and the total time during which abnormal sea conditions prevailed may be obtained. Copies of the marigrams obtained are included in this report as figure 1, jj–rr, in rear pocket.

The most notable thing from Valparaíso northward was that the waves of greatest amplitude did not occur on 22 May as one might suspect, but on 24 May. One explanation might be the influence of new earthquakes that occurred in this same zone

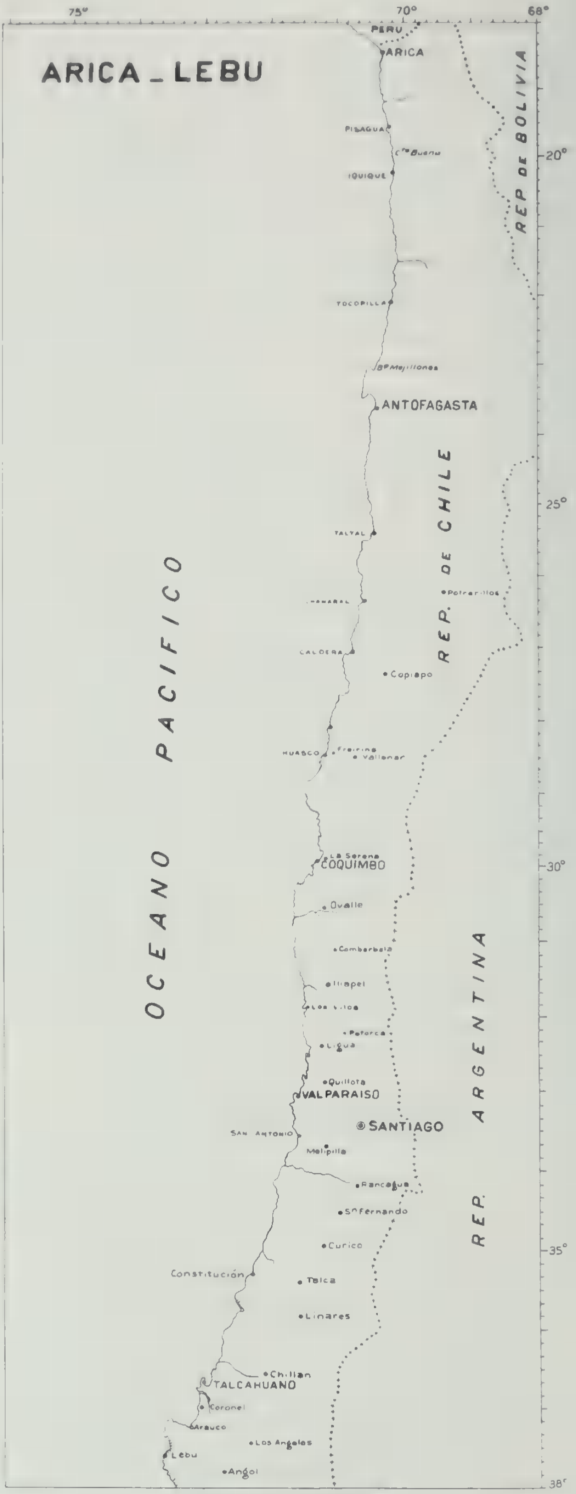

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Fig. 63. Localities of Chile from Arica to Lebu.

or a little farther south. Another possible explanation is that the greatest amplitudes might have arisen from the superposition of maremotos reflected from the Asiatic coast.

The waves had different amplitudes in different ports, clearly showing the influence of submarine topography.

In Talcahuano the waves reached the greatest height, about 3 meters above mean sea level. The water did no damage except for inundation.

One noticeable thing is that, contrary to the observations made more to the south, the first movement in all these ports was an elevation of the water.

TABLE 1

RESUMÉ OF DATA FROM VARIOUS PORTS[a]

Item	Talcahuano	Valparaíso	Coquimbo	Caldera	Antofagasta	Arica
Maremoto arrival time, hr	1609	1616	1639	1712	1745	1836
Travel time of maremoto, hr & min (reckoned from 1510 hr)	00 59	01 06	01 29	02 02	02 35	03 26
Height of 1st wave, m	1.90	0.65	0.83	0.50	0.38	0.80
Time for 1st wave to reach max. height, min	27	13	18	21	21	18
Lowering of water after 1st wave, m	2.42	0.78[b]	1.19	0.52	1.66	1.56
Height of 2nd wave, m	0.62	0.58	1.00	0.32	0.79	1.60
Period between 1st and 2nd waves, min	39	44	38	32	48	54

[a] Tidegrams are repoduced as figure 1 in rear pocket.

[b] Remained stationary at 0.66 meters, then continued lowering.

We include in table 1 the data for the several ports, beginning at the time the effects were first felt. The position of each of these ports is indicated in figure 63.

PART IV. ABNORMALITIES OF THE TIDES OF CHILOÉ AND LLANQUIHUE IN RELATION TO THE EARTHQUAKE OF 22 MAY 1960

INTRODUCTION

The interior maritime zone between Chiloé and Llanquihue, bathed by the Golfo Ancud, Golfo Corcovado, and Seno Reloncavi, is characterized by the great tidal amplitudes measured in its ports. These amplitudes vary between 5 and 7.4 meters. These great ranges, when compared with those of Chilean ports bathed directly by the Pacific Ocean where the amplitude fluctuates between 1.6 and 2.0 meters, show the great difference in this important oceanographic factor between the two zones.

The great amplitude of the tides has given to the interior ports of Llanquihue and

Chiloé a special character, which has been used to advantage economically, industrially, and artistically by the inhabitants of the zone.

Before the earthquakes, the tides were not abnormal, and the high tides of the syzygy, those tides at the days of new and full moon, did not seem extraordinary to the coastal population.

For example, in Quellón (figure 4, 7, 8, and 13), a port situated on the south of Isla Grande de Chiloé, the highest tides of the year (those that occur at the double coincidence of syzygy with the moon in perigee) reach a fraction of a meter over the high tides of the month. This phenomenon formerly escaped notice because the water never passed above the level of the sea wall; on the dock situated to the west of the bay, whose platform is almost at a level with the wall, the water formerly rose only one or two rungs more up the access ladder to the platform, without attracting the attention of the occupants. Thus the highest tides had never before occasioned problems for the population.

Following the earthquakes of May, 1960, the panorama changed.

The tides of the first week of July and of August completely covered the sea wall and inundated the Avenue. This same phenomenon occurred in Queilen, Chonchi, Castro, etc.

The question arises, what happened to Chiloé? The only response is that the insular platform has subsided because of the violent earthquake of May. A good approximation of the amount the insular platform has settled may be obtained in Quellón; the freeboard of the dock was 1.5 meters and the water rose 0.71 meters above the dock; hence, the sinking of the bottom in Quellón is about 2.21 meters. The sinking of the insular platform, different in different places, is a definite fact in the zone of Chiloé; on the other hand, in such ports of the continent as Chaitén, Ayacara, etc., this phenomenon did not cause alarm and the sinking was less.

This alteration of the depth of the sea, a disaster for the population, was of benefit to the ports; because of the increased depth the ships now have a greater maneuvering area.

OBSERVATIONS

In the last week of July 1960 the B. A. PILOTO PARDO departed on an 18-day cruise, making tidal observations in various ports of the interior of Chiloé. Thirty-three localities were visited, from Tenaún in the north to Melinka in the south, returning by the continental ports and adjacent islands.

The effects produced by the high tides were very noticeable. Coastal towns were flooded, and roads and trails at the edge of the beach, passable even during the highest tides before the earthquake, had now disappeared. In the middle of the patio of the school at Ahoni, for example, the new line of the high tides may be seen clearly traced by a line of algae, scraps, and shavings. In all the localities of the island the high tide line is now between 10 and 15 meters farther inland than before.

In Quellón, the port most affected by the high tides, observations were made between 4 and 7 August with a tide scale located in the dock, then undergoing repairs. The platform of the dock coincided with the 6.00-meter mark on the tide scale. Observations were begun at 1000 hours when a tidal altitude of 6.02 meters covered the dock totally. The Port Construction official, in charge of repairs, averred that the dock was constructed so that, formerly, during the highest tides it had had 1.5 meters of freeboard. Now, lacking 3 days before the highest tide, the dock was already inundated. The day-to-day observations registered an increase in tide scale reading as is indicated by the table below.

Aug	Hour	Height of high tide on scale, m
4	1025	6.02
5	1118	6.36
6	1303	6.52
7	1303	6.71

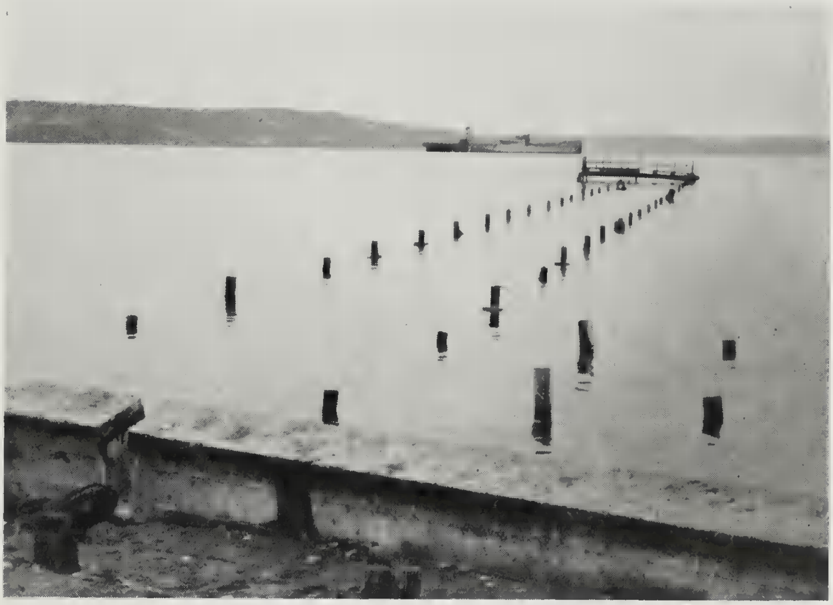

FIG. 64. The Destroyed Dock of Queilen and the Sea Wall, before High Tide, 7 August 1960.

In the port of Queilen (fig. 4 and 64–66), where the same phenomena occurred, the inhabitants were saved from an inundation by the happy chance that a householder had constructed a second dike a little higher than the sea wall and at a short distance from the bases of the houses.

The photographs give various aspects of the port of Queilen on 7 August 1960, the highest tide of the year.

REGIMEN OF THE TIDES OF CHILOÉ

The tide tables of 1960 show that Puerto Montt is the master port, or port of reference, for the zone of Chiloé. The secondary ports Quellón and Queilen are shown below to have a positive time difference with respect to Puerto Montt, i.e., the times of high and low tides in Quellón and Queilen occur 15 and 30 minutes,

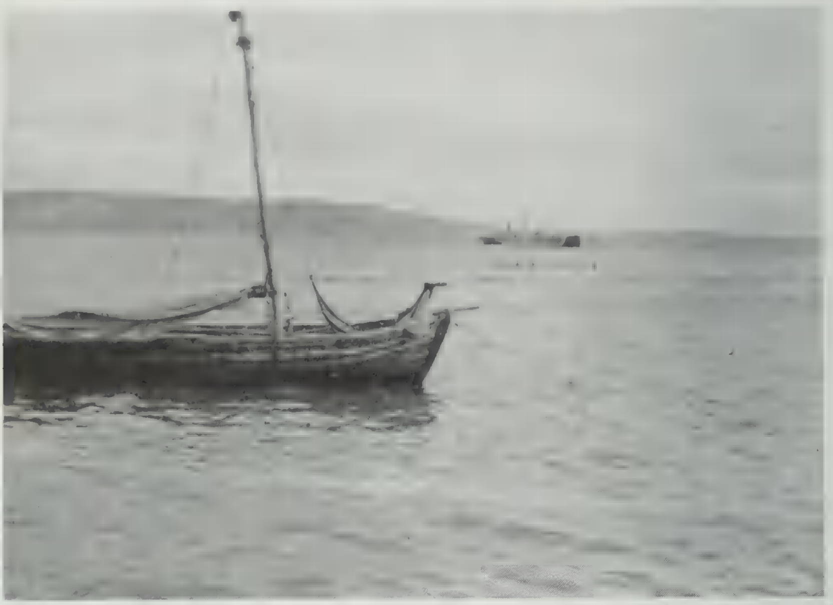

FIG. 65. The Same Zone as in fig. 64 Photographed During Flood Tide on 7 August 1960.

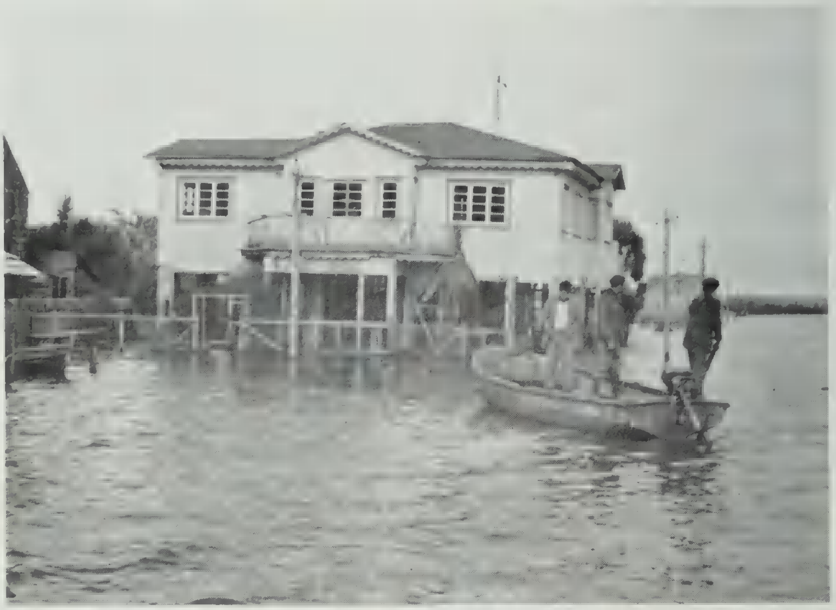

FIG. 66. House in Queilen, the First Floor of Which Has Been Removed Because It Was Flooded Each Time the Tide Came In.

respectively, after those in Puerto Montt. On 7 August 1960 the hour of high tide in Quellón, according to the tide tables, would have been as follows:

Time of high tide, Puerto Montt	1351
Time of high tide, Quellón	1406
Difference, min	15

and in Queilen:

Time of high tide, Puerto Montt	1351
Time of high tide, Queilen	1421
Difference, min	30

The observations made after the earthquake, during August, 1960, showed this sequence to have been altered, as may be seen by comparing once again the hours of high tide at Puerto Montt with those at Quellón and Queilen.

	5 Aug	6 Aug	7 Aug
Time of high tide, Puerto Montt	1200	1255	1400
Time of high tide, Quellon	1118	1203	1303
Difference, min	−42	−52	−57

Before the earthquake the high tide occurred in Quellón 15 minutes after it occurred in Puerto Montt—after the earthquake the high tide occurred 50.3 minutes, on the average, before it occured in Puerto Montt.

The following compares high tide times of Puerto Montt and Queilen on 7 August 1960:

Time of high tide, Puerto Montt	1400
Time of high tide, Queilen	1303
Difference, min	−30

Before the earthquake the Queilen high tide came 30 minutes after that in Puerto Montt; now it happens 30 minutes before.

In this calculation the time of high tide in Puerto Montt has been obtained directly from the portable tide gage located provisionally at Angelmó in Puerto Montt, and the hours of the secondary ports have been taken from observations made with the tide scale in both ports. Although the period of observation is relatively short it may be seen that the times of the tides in this zone have been affected by the earthquakes.

An examination of the map of Chiloé gives us a probable explanation of this change of time. With the descent of the insular or maritime platform, the mass of water in the zone between Corral and Guafo has been increased. The velocity of a tide varies as a function of depth in accordance with the formula $V = (pg)^{1/2}$, where p is the depth and g the acceleration of gravity; hence, velocity is greater in deeper waters. It is perfectly reasonable to suppose that the velocity of translation of the tide wave has undergone an augmentation along the west coast of Isla Grande de Chiloé, as the tide runs through this zone without being opposed by geological obstacles until arriving by Boca del Guafo. On the other hand, the branch of the current that bifurcates near Chacao takes longer to get to Puerto Montt, because it has to cross shallows and make its way past the topographic accidents of Seno Reloncaví.

In order to verify this alteration in time, we can make a comparison of the interval between the tide and the passage of the moon (Establishment of the Port at Quellón before and after the earthquake).

Along the beaches of Chiloé, the Establishment of the Port increases from north to south; for this reason we affirm that the wave of advance of the tide has this direction.

Port	Establishment of Port, hr & min
Arica	08 32
Antofagasta	08 46
Valparaíso	09 45
Talcahuano	10 05
Ancud	11 40
Puerto Montt	00 31

We see that the value increases to 12 hours 25 minutes, from whence it returns to zero, because the moon, the body to which the tide-moon interval is referred, has in this lapse passed from the upper to the lower meridian. This interval is known as the semidiurnal lunar period.

To obtain a reliable value of the Establishment of the Port, we examined the Hydrographic Archives and found some tidal observations on three consecutive days, 18 20 November 1938, made by the cutter YELCHO at Quellón:

	Tide-moon interval, hr & min
Before earthquake (Nov. 1938), 3 days of observation	01 04.2
After earthquake (1960), 4 days of observation	12 07.7

From a comparison of the tide-moon interval the difference in the time of tides at the master port and the secondary port may be obtained. This value is given in Part II of the Tide Tables.

	Time, hr & min
Puerto Montt tide-moon interval	00 31
Semidiurnal period	12 25
Present tide-moon interval at Quellón	12 07.7
Difference between Quellón and Puerto Montt intervals	00 48.3

According to this, high tide occurs first in Quellón and 48.3 minutes later in Puerto Montt. Comparing earlier the hours of high tide in both ports a result of 50.3 minutes was obtained: both results are quite comparable.

CONCLUSIONS

1. The regimen of the time of the tides has been changed in the interior ports of Chiloé.

2. The insular platform on the interior coast of Chiloé has descended and the depth of the ports has increased.

3. The schedule of tides in Puerto Montt has not changed.

From these conclusions we may expect that future hydrographic work done in Castro, Quellón, Queilen, etc., will show variations with the hydrographic data obtained before the earthquake, including changes in bathymetry, tidal phenomena, and the details of the coastline.

ABSTRACT

This paper details the efforts of the Chilean Navy in warning of the tidal waves that followed the earthquakes of May 1960 and the efforts made to collect information concerning the tsunami. Details of time of arrival, damages, wave height and run up are presented for almost all ports in the affected area beginning at Puerto Aysen and working northward. Changes in water depth, caused by erosion, deposition, and changes in land elevation are reported.

The fates of several ships caught in the great waves are described in detail. Marigrams of the tsunami are given for all available Chilean ports.

The times of high and low tides in the Gulf of Chiloé changed following the earthquakes.

ACKNOWLEDGMENTS

The cooperation of the different maritime authorities, captains and pilots of merchant ships, chiefs of lighthouses, and observers at the tidal stations is sincerely appreciated. The authors also wish to thank Dr. Wolfgang Weischet, Director of the Institute of Geography of the Universidad Austral de Chile, for the information and photographs supplied by him, and Sr. Oscar Arriagada, graphic reporter of the newspaper "El Mercuro," of Valparaíso, for the photographs of Corral and Valdivia.

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THE TSUNAMI OF 23 MAY 1960 IN THE HAWAIIAN ISLANDS

By Doak C. Cox and John F. Mink

ABSTRACT

The tsunami of 23 May 1960 was detected in Hilo Bay at 0007 hours HST and recorded on the Honolulu tide gauge at 0033 HST. Runup heights ranged from 2 to 17 feet except in Hilo where the wave formed a bore and reached 35 feet. Sixty-one people were killed and 282 injured in spite of elaborate warning 5 hours in advance of the arrival of the tsunami.

Damage and effects are discussed for all the Hawaiian Islands and recommendations are made to prevent future catastrophes. A brief history of Hawaiian tsunamis is given.

Introduction

A tsunami was generated off the coast of Chile as an accompaniment of the major earthquake of 22 May 1960. This report describes the nature and effects of the tsunami as it washed the shores of the Hawaiian Islands early the next morning, and compares them with those of previous tsunamis.

The Hawaiian Islands form an isolated archipelago running northwest-southeast over a distance of 1600 miles in the central Pacific Ocean (figure 1). Deep waters surround the islands, and great ocean deeps lie between the general floor of the ocean basin around the Hawaiian Islands and the continental margins of the Pacific basin. The margin of the basin, with but few gaps, is seismically active from New Zealand clockwise to the western coast of South America. No large land masses lie between Hawaii and this seismic rim, and only a few, small, scattered islands lie to the northwest or clockwise to the southeast of Hawaii. Hence, the Hawaiian chain is vulnerable to tsunamis that originate from earth movements along any part of the rim, perhaps particularly the northern and eastern parts.

The first historical record of a tsunami in the Hawaiian Islands was made in 1819, 41 years after the discovery of the islands by Captain Cook. Since 1819, 30 readily identifiable tsunamis have struck the islands (Green, 1946; Macdonald and others, 1947; Shepard and others, 1950; Zerbe, 1953; Macdonald and Wentworth, 1954; Fraser and others, 1959; Eaton and others, 1961), 15 of which have resulted in significant damage. More than half the waves have been derived from faulting

Source direction	Number	Relative damage			
		Severe	Moderate	Small	None
Northeast	2	—	—	—	2
Southeast	7	4	1	1	1
Southwest	2	—	—	1	1
Northwest	14	1	3	2	8
Local	2	1	—	1	—
Unknown	3*	—	—	—	2
Totals	30*	6	4	5	14

* Damage not known for one of tsunamis of unknown source.

in the Kuriles Kamchatka Aleutian region north and northwest of the archipelago, and about one fourth have originated along the South American coast. The origin of three is unknown.

The preceding table summarizes the tsunamis reported since 1819, showing their region of origin and the relative damage caused in the Hawaiian Islands.

This table, except for the last three tsunamis, is adapted from Macdonald and others (1947) and shows that most of the severely damaging tsunamis have come from the southeast quadrant. In order of destructiveness, the zones of origin are (1) southeast quadrant, in which the coast of South America is the principal source; (2) northwest quadrant, in which the Kamchatka-Aleutian region is the chief source; (3) within the Hawaiian chain, probably restricted in origin to the coasts of the island of Hawaii; (4) southwest quadrant, from which only two tsunamis originated, one of which resulted in a small amount of damage and the other in none; and (5) northeast quadrant, from which no damaging tsunamis have been reported.

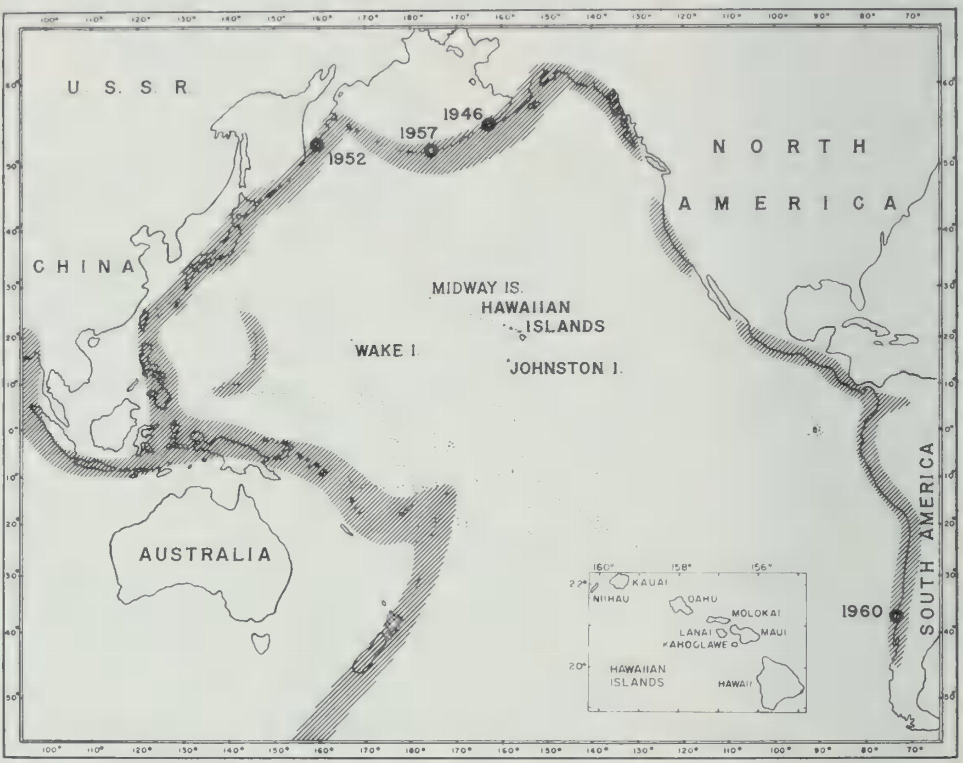

FIG. 1. Index Map of the Pacific Ocean Showing the Hawaiian Archipelago; Epicenters of the Earthquakes Associated with the Tsunamis of 1946, 1952, 1957, and 1960 (Circles); and Seismically Active Belts (Shaded). (Inset identifies the major Hawaiian Islands.)

The disastrous tsunami of 1946, which came from the Aleutian Islands, caused 159 deaths and led to a study of tsunami phenomena by a number of observers in the Hawaiian Islands (Shepard and others, 1950). This tsunami was the first in 69 years to cause severe damage, although moderate damage had been caused by a tsunami in 1923. Since 1946, three additional damaging tsunamis have struck the islands—one from Kamchatka in 1952 and one from the Aleutians in 1957, which caused moderate damage but no deaths; and the May 1960 tsunami from Chile that caused severe damage and 61 deaths.

The general features of tsunamis are well known and have been discussed extensively in the literature. Observations on the Hawaiian tsunamis of the last 15 years indicate that they have average recorded periods of 15 to 40 minutes and travel across the open sea at average speeds of 400 to 500 mph. The maximum recorded height to which the waves have washed the shores of the islands, 55 feet, occurred during the 1946 tsunami. The following table lists some characteristics of the four damaging tsunamis that have struck Hawaii since 1946 and of the earthquakes that were associated with them. The wave heights reported in the table and elsewhere are the runup heights on island shores above mean lower low water, which is about 1 foot below mean sea level.

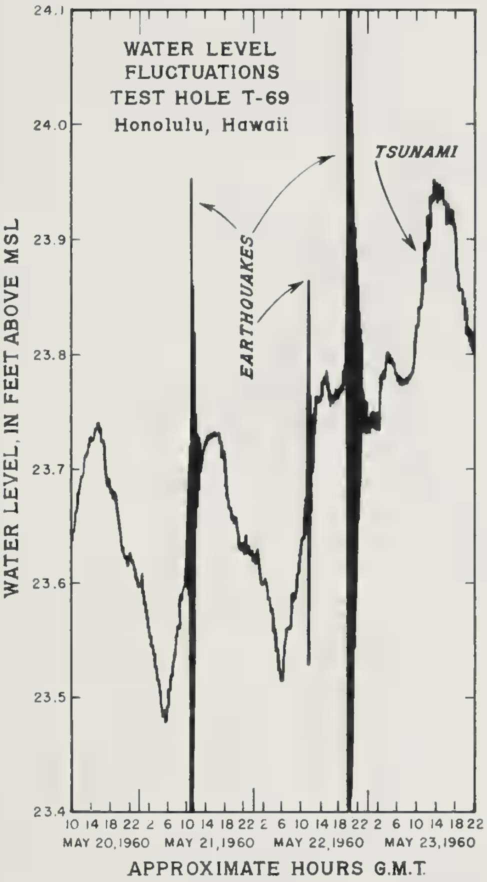

FIG. 2. Hydrograph of Test Hole T-69 in Southern Oahu Showing Fluctuations in Water Level Caused by the Chilean Earthquake and Subsequent Tsunami of May 1960.

Date	Epicenter of earthquake	Magnitude (Richter)	Average speed of tsunami, mph	Average recorded period of tsunami, min	Maximum recorded runup height, ft	Estimated Damage, millions of dollars
4/1/46	53.5N 163W	$7\frac{1}{2}$	490	15	55	25
11/4/52	52.5N 159E	$8\frac{1}{2}$	500	38	20	1
3/9/57	51.3N 175.8W	8	497	18	53	5
5/23/60	41S 73.5W	$8\frac{1}{2}$	445	33	35	25

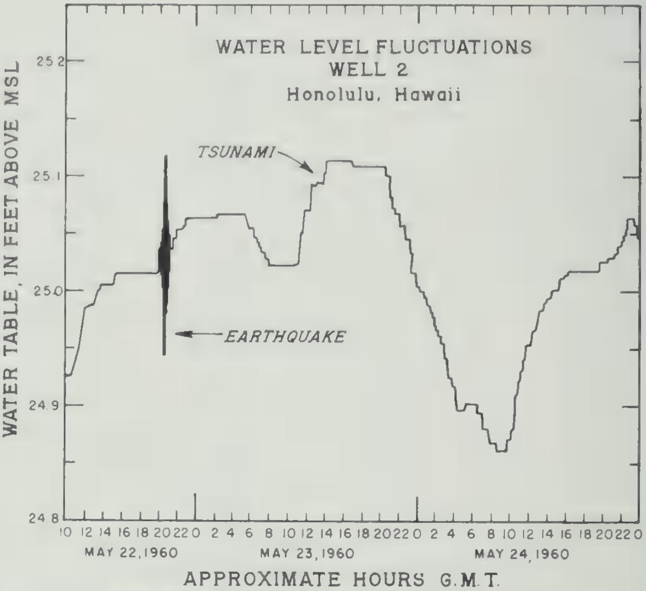

Fig. 3. Hydrograph of Well 2 in Southern Oahu Showing Fluctuations in Water Level Caused by the Chilean Earthquake and Subsequent Tsunami of May 1960.

Hawaiian Records of the Chilean Earthquakes of May 1960

The major Chilean earthquake of 22 May 1960, and its associated foreshocks and aftershocks were recorded by several seismographs in Hawaii. These seismographs are maintained on the island of Oahu by the Honolulu Magnetic Observatory, U. S. Coast and Geodetic Survey and on the island of Hawaii by the Hawaiian Volcano Observatory, U. S. Geological Survey. The shocks also were recorded by water-level oscillations in numerous artesian wells on Oahu (figures 2–4). These wells penetrate the confined portions of aquifers composed of basalt lava flows of the Koolau volcanic series. The range in oscillation in some of the wells exceeded 0.5 foot. Eaton and Takasaki (1959) have suggested, from a study of similar oscillations accompanying previous earthquakes, that the oscillations result from alternate compression and dilation of the aquifer by the passage of the Rayleigh waves of the earthquakes.

The major Chilean earthquake of 1911 hours GMT, 22 May 1960, was accompanied by a T-phase of unusual duration and intensity, as recorded by seismographs on the southeast coast of the island of Hawaii. According to Eaton and others (1961), the amplitude increased over an interval of 5 minutes after the beginning of the record, declined slightly, increased to a second maximum at 7 minutes, and then decreased rapidly.

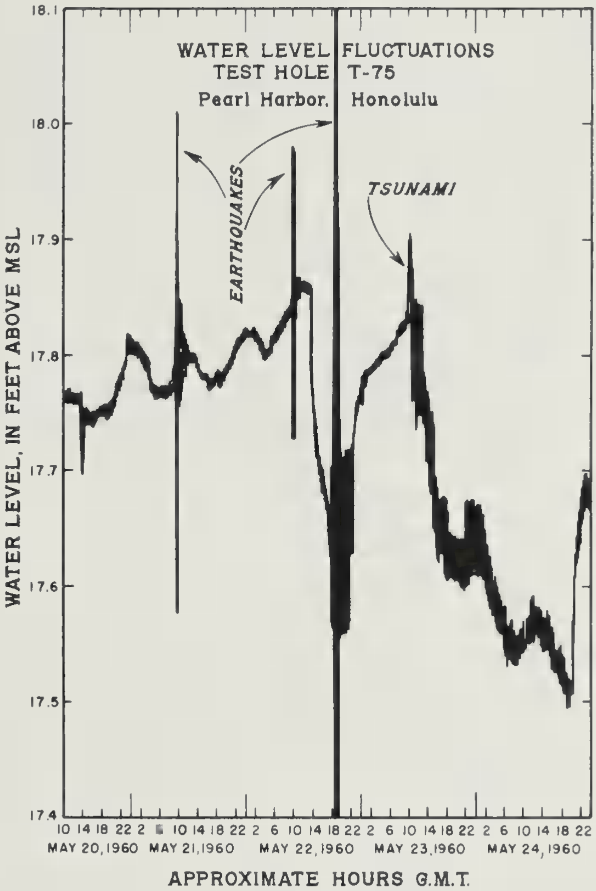

FIG. 4. Hydrograph of Test Hole T-75 in Southern Oahu Showing Fluctuations in Water Level Caused by the Chilean Earthquake and Subsequent Tsunami of May 1960.

The first large foreshock, that of 1003 hours GMT on 21 May, magnitude $7\frac{1}{2}$, was accompanied by a small tsunami detectable in Hilo Bay, Hawaii (Eaton and others, 1961).

The main shock, of magnitude $8\frac{1}{2}$, tripped an alarm attached to a seismograph at the Honolulu Magnetic Observatory, U. S. Coast and Geodetic Survey, at 1938 hours GMT, 22 May (0938 hours Hawaiian Standard Time (HST)). The Observatory personnel commenced an investigation leading to a public advisory bulletin on the possible generation of a tsunami at 1159 hours HST and an official warning of the approaching tsunami at 1847 hours HST (Symons and Zetler, 1960).

The 23 May Tsunami

Arrival times and velocities: The tsunami associated with the major earthquake shock was detected in Hilo Bay at 0007 hours HST (Eaton and others, 1961) and recorded on the Honolulu tide gage at 0033 hours HST (Symons and Zetler, 1960), only 7 minutes and 3 minutes later, respectively, than times of arrival as they were first estimated by the Honolulu Magnetic Observatory. If it is assumed that the tsunami was generated at the time of the principal shock, its travel time was 14.9 hours to Hilo and 15.4 hours to Honolulu. These times indicate average velocities between 440 and 445 miles per hour over the respective 6600- and 6800-mile paths, if the tsunami was generated at the epicenter on the Chile coast. These velocities are consistent with those to be expected on the basis of the depths of the ocean between Chile and Hawaii.

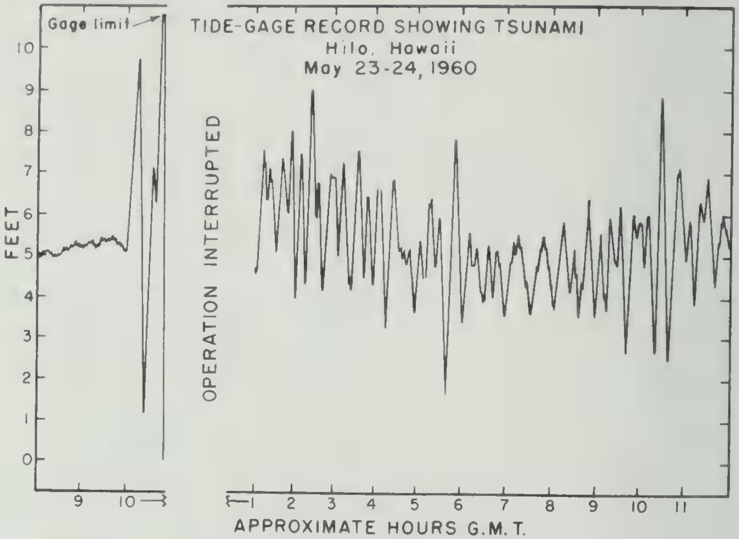

FIG. 5. Marigram for the Tide Gage at Hilo Showing the Initiation of the Tsunami of 23 May 1960. (Modified from Symons and Zetler, 1960.)

Period and relative height of successive waves: As is usual with tsunamis, the period of the May 1960 tsunami varied from place to place and with time at each place. Figures 5–8 (taken from Symons and Zetler, 1960) show tide gage marigrams for the initial tsunami activity at locations in the Hawaiian archipelago and elsewhere in the Central Pacific. Figures 9–11 are plots of observers' records of water levels reached in Hilo Bay, Hawaii; Maalaea Bay, Maui and Hanapepe Bay, Kauai. As usual, the earliest part of each record appears the simplest, and the later parts become complicated by the interference of waves following different paths and by the resonance of the immediate coastal area. The following table shows the intervals between the first and second crests on tide gage records, as a parameter of the simplest motion, tabulated by the U. S. Coast and Geodetic Survey (Symons and Zetler, 1960). These values are supplemented in the table by values obtained by observers at several additional points on Hawaiian shorelines.

Place	Lat. N	Long. W	Time of arrival, GMT	Period, 1st to 2nd crest, min	Observer
Hilo, Hawaii	19°44′	155°03′	0958	33	Tide gage
Hilo (Wailuku Bridge)	19°44′	155°05′	1007	36	Eaton *et al*
Maalaea, Maui	20°48′	156°31′	1033	32	C. Marsh
Mokuoloe Island, Kaneohe Bay, Oahu	21°26′	157°48′	1040	87	Tide gage
Honolulu, Oahu	21°18′	157°52′	1033	33	Tide gage
Honolulu (Black Point)	21°15′	157°48′	—	±30	D. Cox
Nawiliwili, Kauai	21°57′	159°21′	1040	25	Tide gage
Port Allen, Kauai	21°54′	159°36′	≤1051	≥30	L. Nishikawa
Midway Island	28°13′	177°22′	1330	24	Tide gage
Johnston Island	16°45′	169°31′	1130	54	Tide gage
Wake Island	19°17′	166°37′E	1333	13	Tide gage

The fundamental period of tsunamis is a point of considerable disagreement. Munk and Snodgrass (1960) have demonstrated the dominant importance of local resonance in records with durations of 2 days. Van Dorn (1959) believes that the

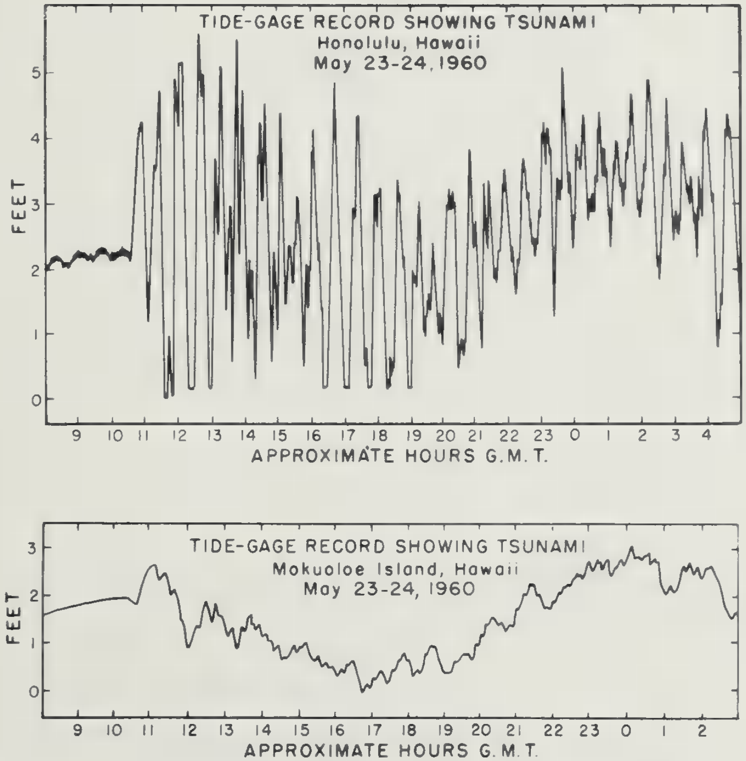

FIG. 6. Marigrams for the Tide Gages at Honolulu, and Mokuoloe (Coconut) Island, Oahu, Showing the Initiation of the Tsunami of 23 May 1960. (Modified from Symons and Zetler, 1960.)

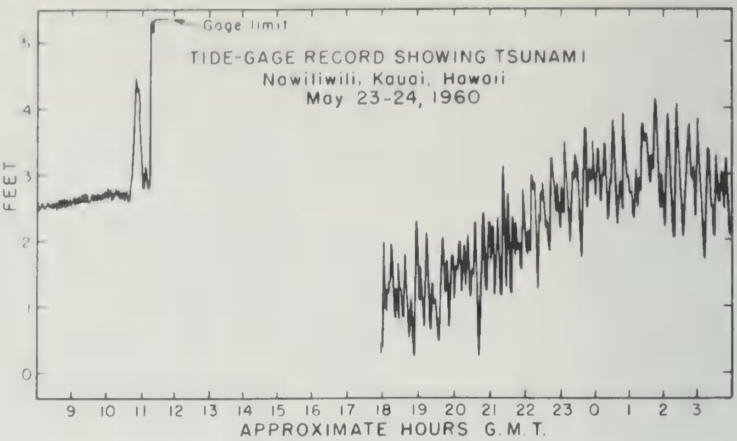

FIG. 7. Marigram for the Tide Gage at Nawiliwili, Kauai, Showing the Initiation of the Tsunami of 23 May 1960. (Modified from Symons and Zetler, 1960.)

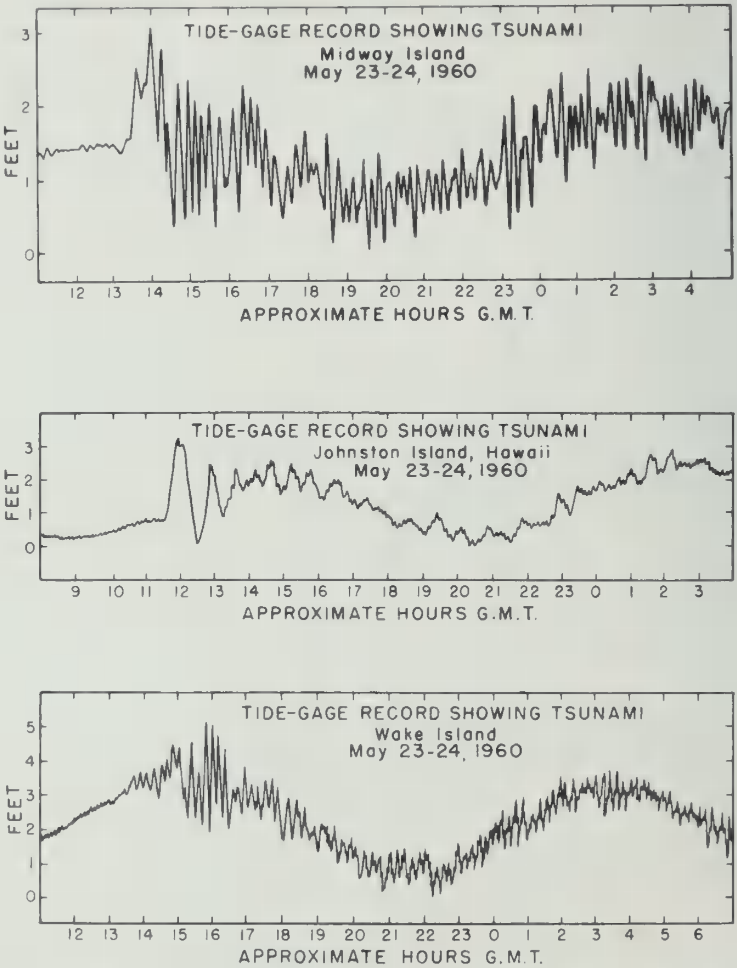

FIG. 8. Marigrams for the Tide Gages at Midway, Johnston, and Wake Islands. (Modified from Symons and Zetler, 1960.)

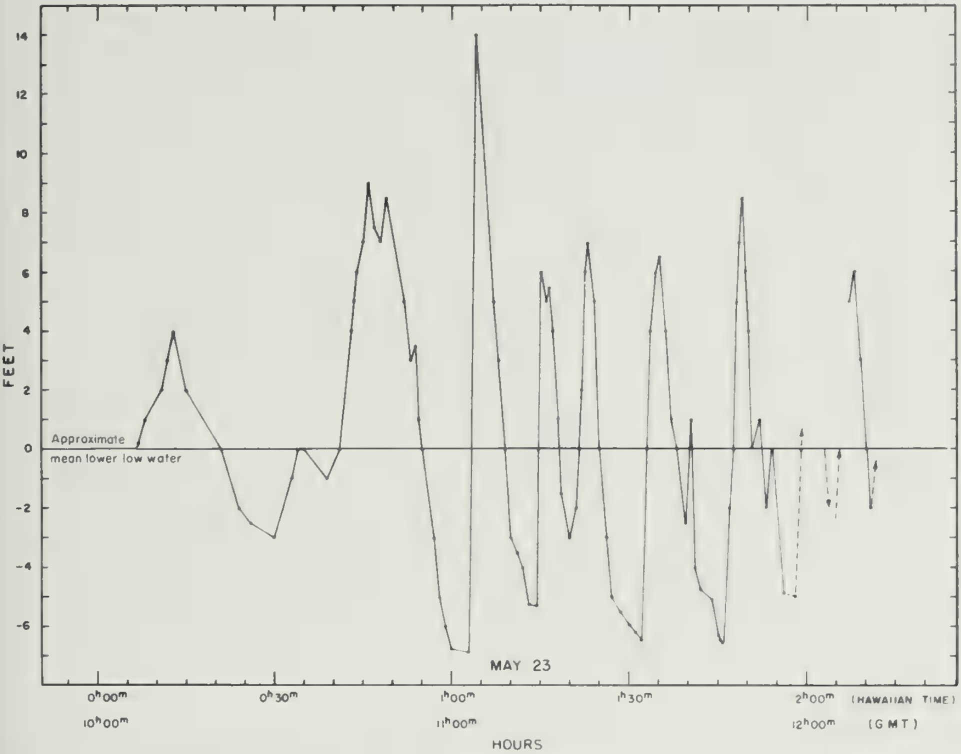

FIG. 9. Water Levels as Observed at Wailuku Bridge, Hilo Bay, Showing the Initiation of the Tsunami of 23 May 1960. (Modified from Eaton and others, 1961.)

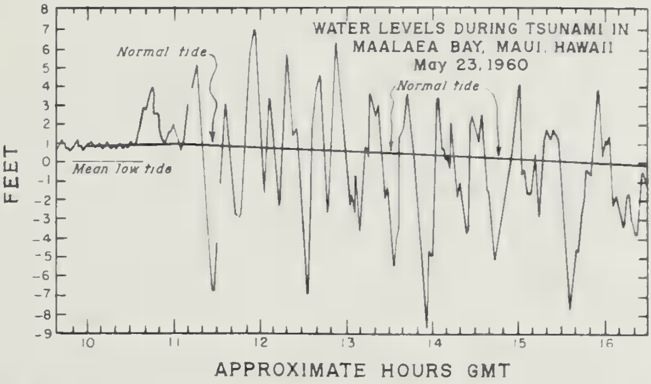

FIG. 10. Water Levels as Observed in Maalaea Bay, Maui, by Clifton Marsh, Showing the Initiation of the Tsunami of 23 May 1960.

fundamental period is commonly less than 10 minutes. Others consider that the longer periods recorded, sometimes equaling or exceeding 2 hours, are the fundamental ones. The motion in the ocean could quite possibly be better described by a spectrum of some complexity than by a single dominant period.

In all the Hawaiian records of the 1960 tsunami the first significant feature is a crest, although an earlier slight trough is suggested on some records. The highest crest and maximum range were associated generally with the third or fourth wave, although the first wave was the largest in the long-period record from Mokuoloe Island in Kaneohe Bay, Oahu.

Considerable wave action persisted for many days after the first arrival of the tsunami. In general the later amplitudes did not approach those of the first waves, but a wave reaching 8 feet was observed by members of a U. S. Geological Survey team on the northeast coast of Oahu 14 hours after the first wave arrived. The continuous wave action was responsible for a second official tsunami warning about noon on 25 May, following one of the aftershocks of the main earthquake in Chile.

In general the wave action along Hawaiian shores was quiet, resembling that of the tide, although it had a shorter period and a greater range. Superimposed on the tsunami crests, the ordinary swell and chop attacked parts of the shorelines above their normal reach; otherwise horizontal velocities generally became significant only where appreciable areas were flooded. In Hilo Bay, however, the third wave was converted into a bore. Tremors recorded by a seismograph in Hilo and observations by Eaton and others (1961) indicate that the breaking occurred well out in the bay. They estimate that the velocity of the bore was between 40 and 45 fps.

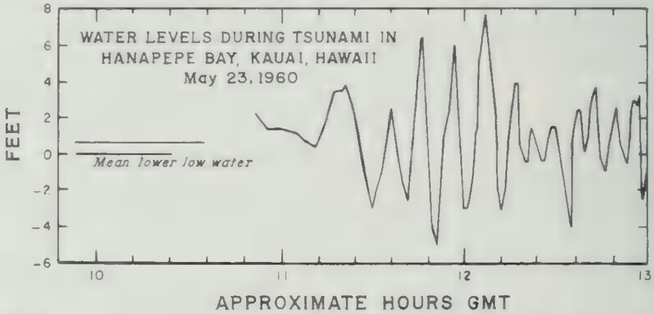

FIG. 11. Water Levels as Observed in Hanapepe Bay, Kauai, by Larry Nishikawa, Showing the Initiation of the Tunami of 23 May 1960.

Runup heights reached by the tsunami: The heights to which the waves of a tsunami will reach are governed by a complex of processes that is controlled by the submarine topography, the shoreline configuration, and the roughness of the bottom in shallow water and of the land surface in the area inundated. The heights to which the tsunami waves would reach themselves can be augmented by the heights of the superimposed wind-generated waves. As indices of the magnitude of the tsunami in the ocean, runup heights are of only qualitative value. However, they constitute direct indices of the shoreline zones subject to damage. Runup heights were measured around the shorelines of most of the islands in 1960, as they had been in 1946, 1952, and 1957, to obtain a qualitative indication of the energy distribution in the waves at sea and a record of coastal zones affected.

The runup heights, shown in figures 12–15, were measured to swash marks; lines of debris; limits of salt-killed vegetation; trash left hanging from trees, fences, etc.; and limits of abrasion and staining on trees and buildings. Most of the heights were measured to the land edge of the inundated area, but a few represent the maximum height reached by the waves at some point between the shore and the land edge, from which the water levels declined inland. Measurements were made from tide level by hand leveling or horizon sighting, using a steel tape or assistant's stature, and the heights were later corrected to mean lower low water. In some areas the density of measurements was too great for plotting, and only representative values are shown.

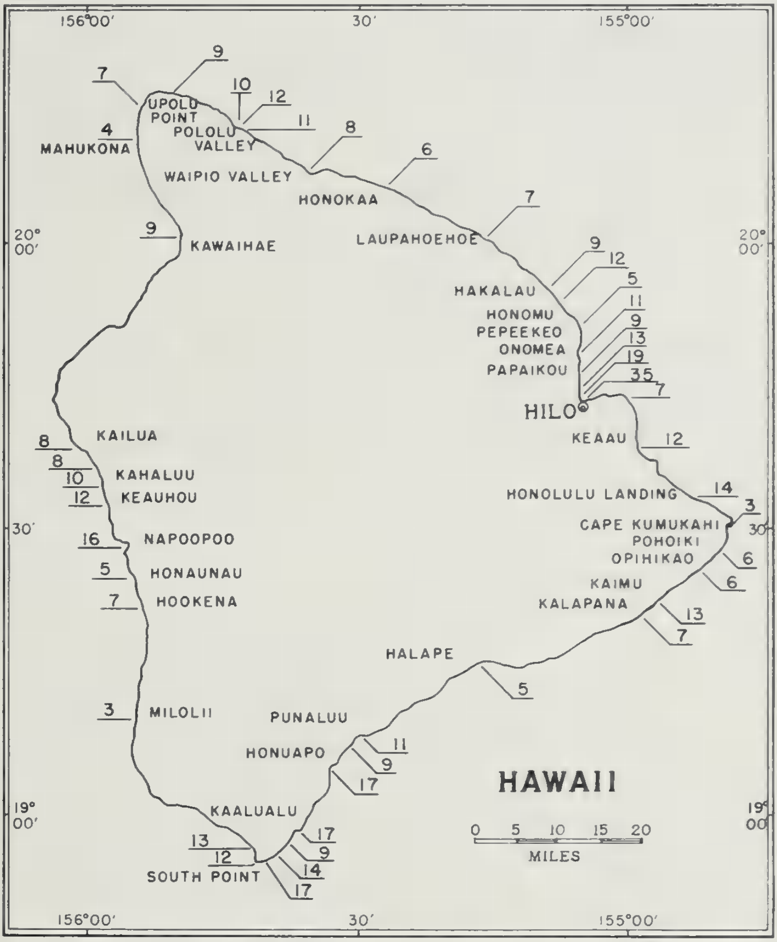

FIG. 12. Map of the Island of Hawaii Showing Runup Heights in Feet Above Mean Lower Low Water During the 1960 Tsunami.

Except in the vicinity of Hilo, the runup heights in the 1960 tsunami in general ranged from 2 to 17 feet, considerably lower than those of the 1946 Aleutian tsunami but comparable with those of the 1952 Kamchatka and the 1957 Aleutian tsunamis. The 1960 heights were relatively uniform, particularly in comparison with the 1946 heights. The heights averaged about 9 feet on Hawaii, 10 feet on Maui, 7 feet on

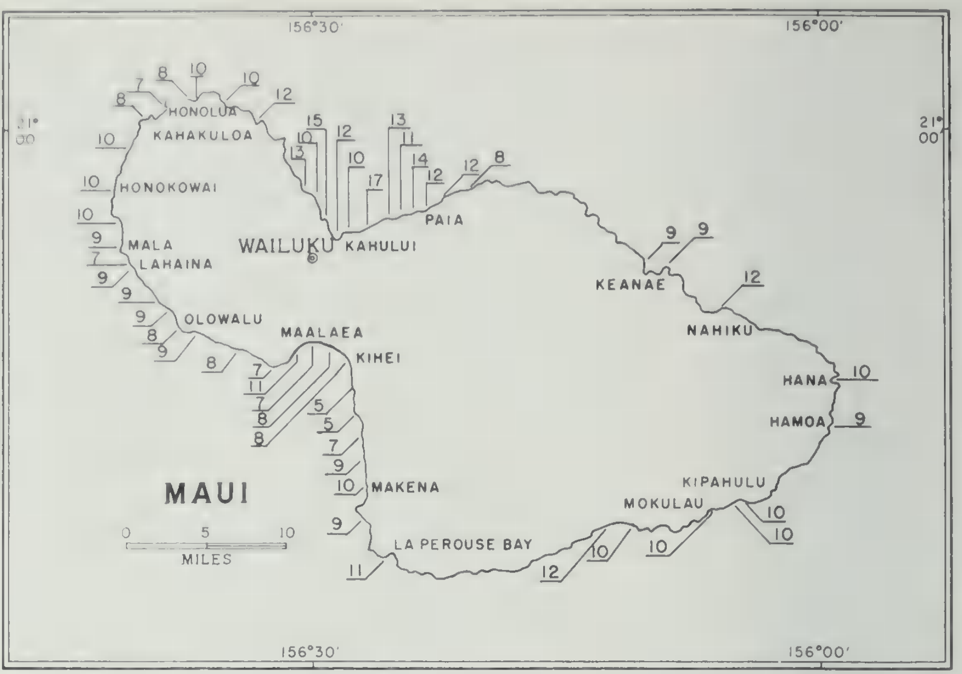

Fig. 13. Map of the Island of Maui Showing Runup Heights in Feet Above Mean Lower Low Water During the 1960 Tsunami.

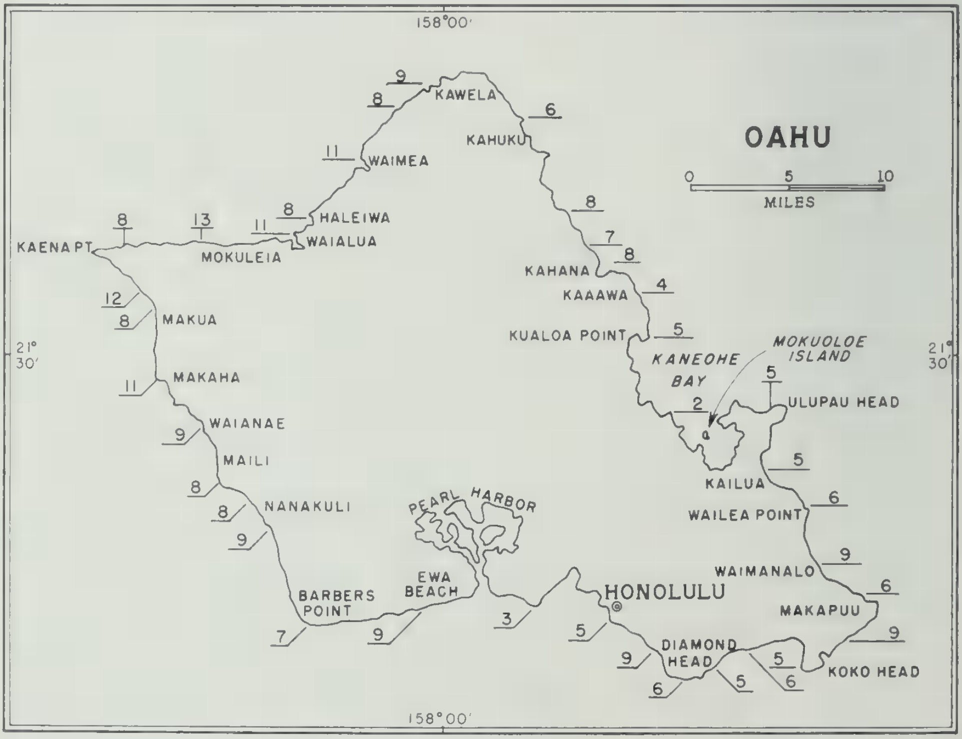

Fig. 14. Map of the Island of Oahu Showing Runup Heights in Feet Above Mean Lower Low Water During the 1960 Tsunami.

Oahu, and 8 feet on Kauai. There was no pronounced directional effect: in fact, on Oahu, the coastline with the greatest average runup height was that facing northwest, directly away from the waves coming from Chile. The contrast in heights and their variability on the island of Oahu may be seen from the runup values for the 1946, 1952, 1957, and 1960 tsunamis shown in figure 16.

In the vicinity of Hilo, where lower than average heights had been experienced in 1946, the 1960 heights were greater than anywhere else in the islands, reaching a maximum of 35 feet near the waterfront south of the end of the breakwater. The maximum height at the limit of inundation was about 20 feet. Runup heights and inundation areas for the 1946 and 1960 tsunamis are contrasted for the Hilo area in figure 17. The pattern of 1960 heights suggests the possibility of interference between the incoming bore of the third wave and a wave reflected from the east end of the bay. The great runup heights experienced at Hilo in 1960 seem the more remarkable because Hilo is sheltered by Cape Kumukahi (fig. 12) from the direct approach of waves from Chile.

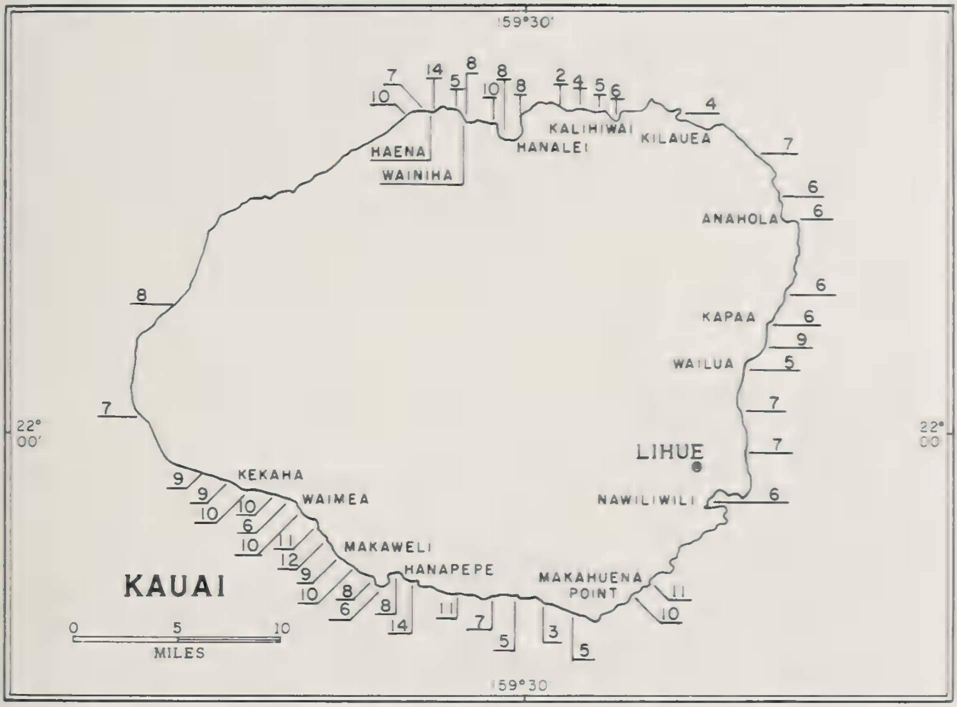

Fig. 15. Map of the Island of Kauai Showing Runup Heights in Feet Above Mean Lower Low Water During the 1960 Tsunami.

Casualties and damage: The tsunami caused 61 deaths by drowning or crushing, and 282 persons sustained injuries requiring medication or hospitalization, all in the city of Hilo. All this was in spite of the issuance of an official warning by the Honolulu Magnetic Observatory more than 5 hours before the arrival of the tsunami and the public dissemination of the warning by the Civil Defense Agencies and police via radio, television, fixed and mobile sirens, public address systems, and wardens. A study of the behavior of the residents of the inundated area, made under the auspices of the Hawaiian Academy of Science (Bonk and others, 1960), revealed that only a third of the people evacuated to high ground. The reasons for the failure of the warning to have the desired effect may be summarized in general by the statement that the information reaching the people was not sufficiently clear and precise to give them, with their previous understanding of the nature of the risk, a definite sense of appropriate response or an adequate feeling of urgency.

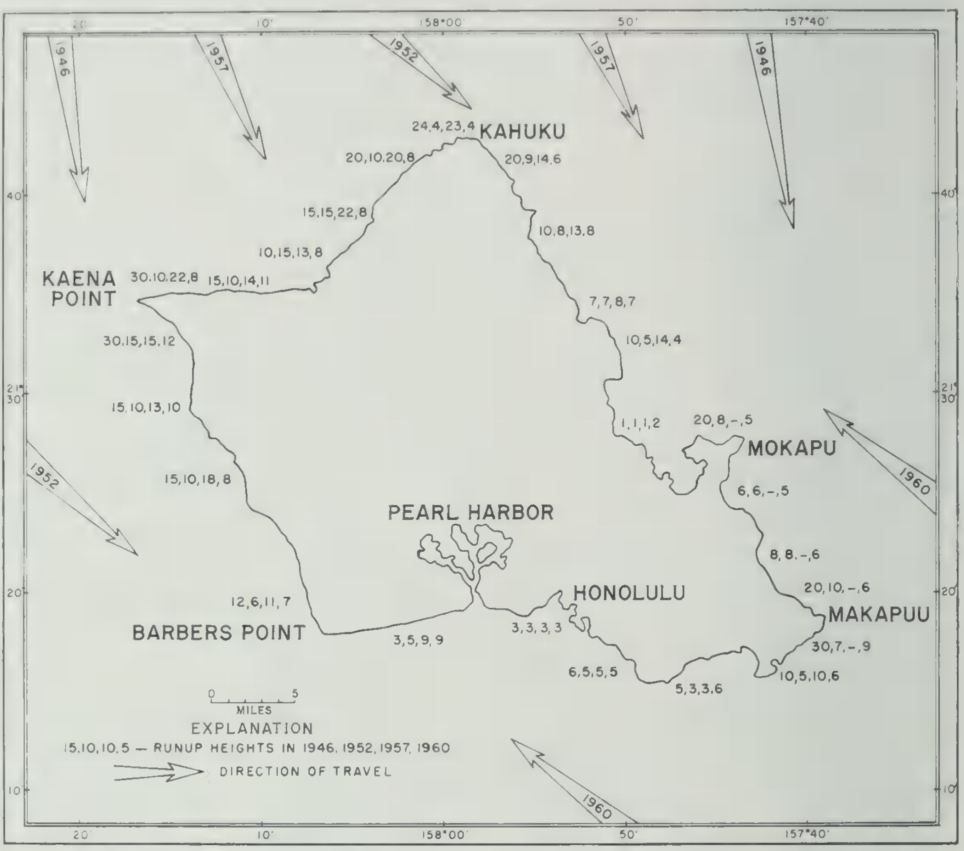

FIG. 16. Map of the Island of Oahu Showing Runup Heights in Feet and Directions of Approach of the 1946, 1952, 1957, and 1960 Tsunamis.

By far the major part of the physical damage caused by the tsunami also occurred in Hilo. Nearly 600 acres inland of the harbor were inundated, some of the area extending to the 20-foot contour above sea level. In nearly half of this area the destruction of buildings was almost complete (Eaton and others, 1961). In the area of maximum destruction, only buildings of reinforced concrete or structural steel, and a few others sheltered by these buildings, remained standing—and even these were generally gutted. Frame buildings either were crushed or floated away nearly to the limits of flooding. Dozens of automobiles were wrecked; an 11-ton

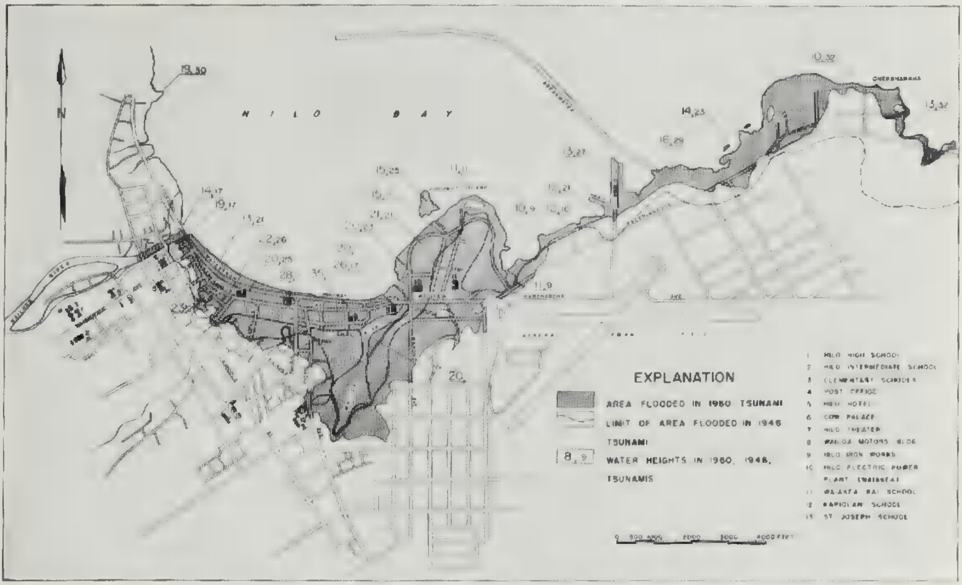

FIG. 17. Map of Hilo Harbor Showing Runup Heights During the 1946 and 1960 Tsunamis. (From Eaton and others, 1961.)

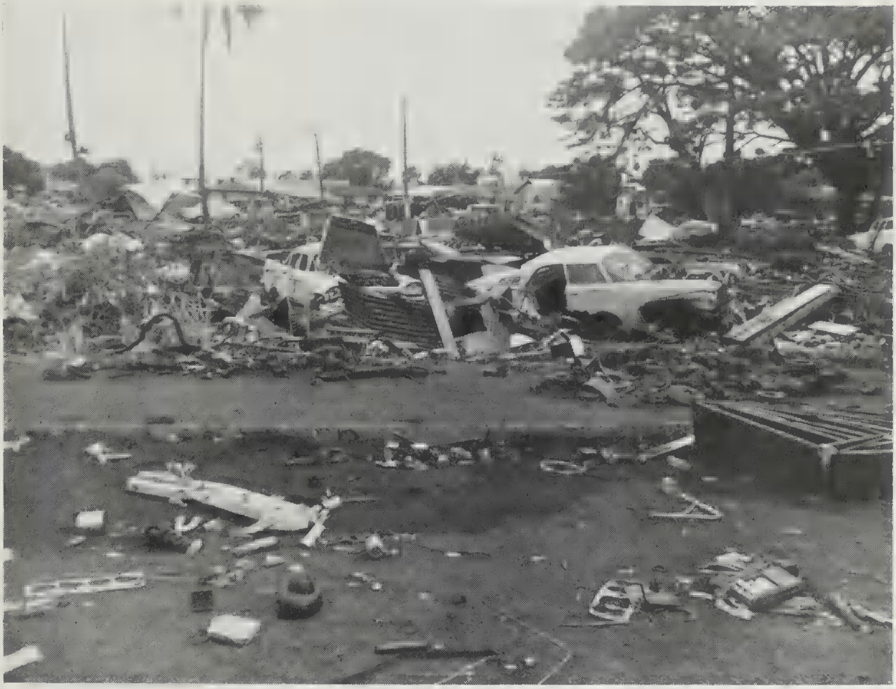

FIG. 18. Chaotic Mass of Debris, Including Automobiles, Houses, and Machinery, Left by the 23 May Tsunami in the Waiakea Section of Hilo. (Photo by Hawaiian Volcano Observatory, U. S. Geological Survey.)

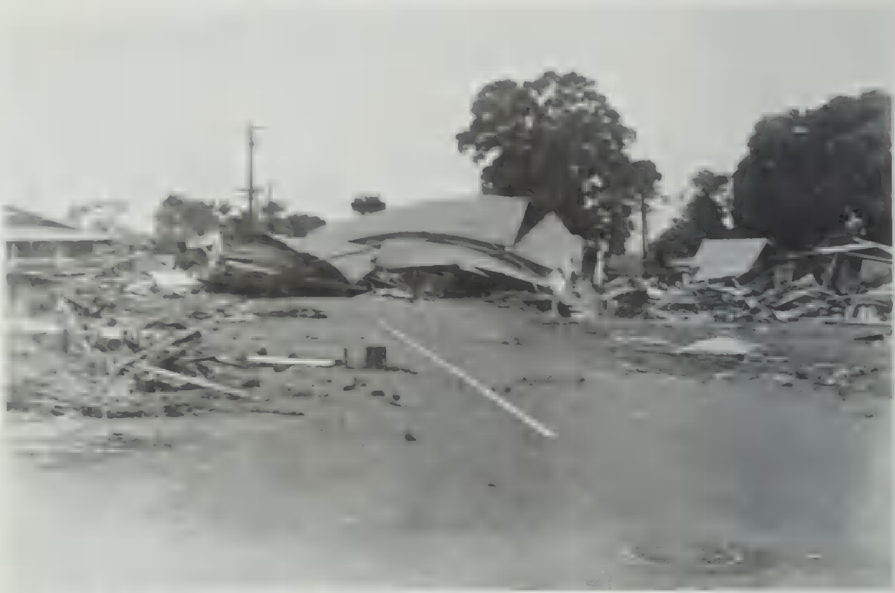

FIG. 19. Large Building Carried Across a Street by the 23 May Tsunami in the Waiakea Section of Hilo. (Photo by Hawaiian Volcano Observatory, U. S. Geological Survey.)

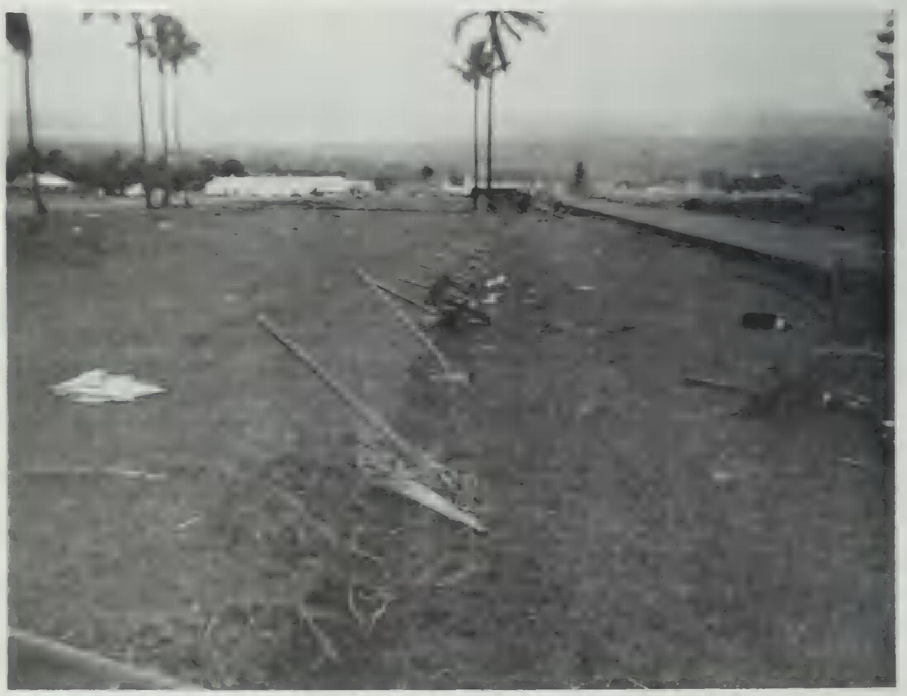

FIG. 20. View Looking West Along the Hilo Bay Front Highway Showing Fence Posts Bent by the Force of the 23 May Tsunami. The area behind the palm trees on the extreme left has been swept clean of its buildings. (Photo by Hawaiian Volcano Observatory, U. S. Geological Survey.)

tractor in a showroom was swept away; heavy machinery, mill rollers, and metal stocks were strewn about. Rocks weighing as much as 22 tons were plucked from a sea wall and carried as far as 600 feet inland. The nature of the destruction is illustrated by several photographs (figures 18–21).

Damage elsewhere on the island of Hawaii was restricted to the west and southeast coasts, where about a dozen buildings, mostly of frame construction, were floated off their foundations, crushed, or flooded.

On Maui the damage was concentrated in the Kahului area on the north coast. Although Kahului Harbor is protected by two breakwaters with a narrow entrance between them, the water rose on the shores of the harbor to 12 feet above sea level and swept back more than 2500 feet from the shore into the town. A warehouse and half a dozen houses were demolished, and other warehouses, stores, offices, and houses, and their contents were damaged. Other buildings were damaged at Paukukalo, just outside and west of the harbor. At Spreckelsville and Paia, east of Kahului, houses were damaged and one house at each place demolished. Additional damage occurred at Kihei on the south coast and at Lahaina on the west coast.

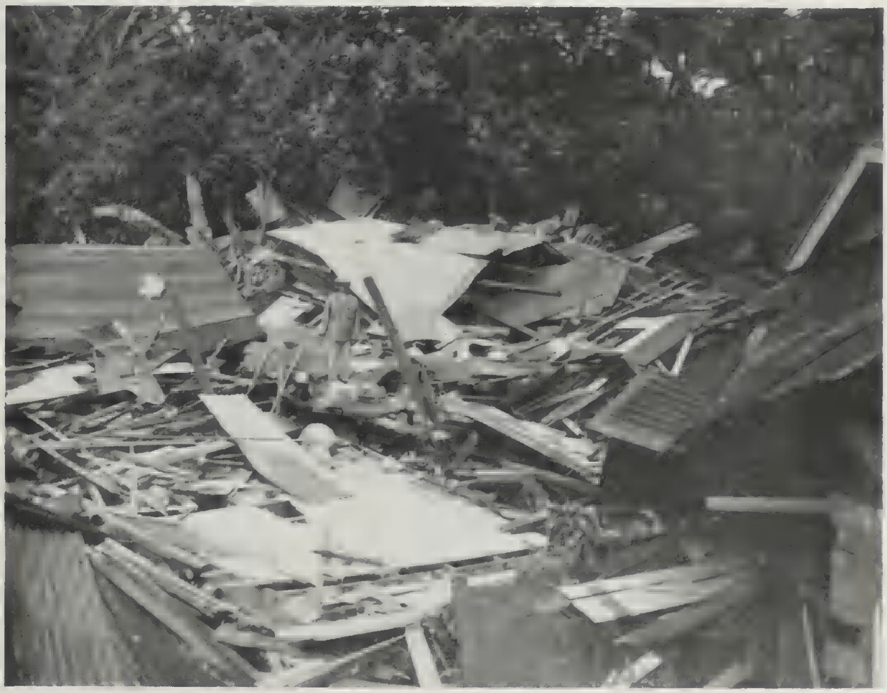

FIG. 21. The Remains of a Residential Area in Hilo After the 23 May Tsunami. (Photo by Robert Haugen, U. S. National Park Service.)

On the island of Molokai there was some damage to houses, fish ponds, and roads, and on the island of Lanai a beachhouse was demolished.

The islands of Kauai and Oahu escaped with only minor damage. Houses at

Kuliouou, an eastern suburb of Honolulu, were flooded. Elsewhere on Oahu no damage was reported, even where there was inundation of areas occupied by houses. On Kauai, so far as is known, the only damage consisted of one frame building being floated off its foundation on the south coast.

PREPARATIVE MEASURES FOR FUTURE TSUNAMIS

The casualties in Hilo during the May 23 tsunami indicate that the tsunami warning system, despite its technical success, did not function satisfactorily in its primary purpose of inducing people to leave areas where risk is high when a tsunami is approaching. A number of improvements are planned. The U. S. Coast and Geodetic Survey has taken steps to increase the number of tide stations reporting to the Honolulu Magnetic Observatory. The Civil Defense communications network is being improved. A tighter control of the information broadcast by radio and television stations has been assured and formal evacuation zones are being outlined. A program of research on tsunamis has been established at the Hawaii Institute of Geophysics. Most importantly, however, an understanding by the public of the nature of and risks from tsunamis must be created and maintained through continuing education.

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THE TSUNAMI OF 22 MAY 1960, IN THE SAMOA AND COOK ISLANDS

By J. G. Keys

ABSTRACT

The tsunami which reached islands of the Samoan group at approximately 2035 hours local time, 22 May 1960, was undoubtedly one of the largest that has been recorded in the group. Generated by a large earthquake off the coast of Chile (near 41°S, 73½°W) at 1911 hours Greenwich Mean Time (GMT), 22 May, the tsunami was responsible for widespread damage throughout the Pacific.

This paper discusses observed features of the tsunami at various locations in the three principal islands of the Samoan group, and Tables 1–3 summarize this data in approximate chronological order. Table 4 tabulates seismic data recorded at Afiamalu, Western Samoa, on 21, 22, and 25 May, GMT. Table 5 presents a brief résumé of previous tsunamis recorded in the group.

The characteristics of the tsunami observed at Rarotonga in the Cook Islands are also described.

Introduction

The Samoan archipelago (fig. 1) is a chain of islands approximately 300 miles long, lying between 168°08′ and 172°50′W longitude and 14°33′ and 13°20′S latitude, about 1,500 miles north-northeast of New Zealand and 500 miles east of Fiji. The three main islands in the archipelago are those of Savai'i and Upolu, Western Samoa, and Tutuila, American Samoa.

In general, the individual island coastlines are bounded by reefs, of either the barrier or fringing type, although in certain areas these have been overridden by lava flows. Detailed bathymetry of the area is sparse, but the general picture (Kear and Wood, 1959) is that of one or more offshore shelves that slope gradually to depths of 50–100 fathoms. Beyond these the sea floor falls away relatively steeply down to and beyond 500 fathoms.

It is evident that the submarine features of the group, combined with the general presence of an offshore reef, have a profound effect on the behavior of tsunamis reaching the shoreline proper. At coastlines screened by reefs, the 1960 tsunami commonly manifested itself as a series of short-period surges, rather than the long-period activity normally associated with such phenomena; in such cases, striking wave amplitudes were not observed.

At Fagaloa Bay (fig. 2) and Pago Pago Harbor (fig. 3), however, the normal behavior pattern was more evident; bathymetric profiles up these relatively long bays show a gradually sloping sea floor that reaches a depth of approximately 40 fathoms at the mouth of the bays. Detailed offshore data are not available for Fagaloa Bay, but it seems probable that it is entirely unscreened by reefs. Pago Pago Harbor is partially screened, directly out from the mouth of the bay.

The great-circle distance from the epicenter to Pago Pago Harbor is 5,937 miles. The travel time, calculated from the Pago Pago marigram (figure 4), is 12 hours 24 minutes, giving a mean velocity of 702 ft/sec. This is slightly higher than the velocity calculated for the Chile-Apia path, due in part to the time lag resulting from the placement of the Apia Observatory tide gage inside the reef, and in part to a suspected clock lag at the gage.

For a uniform ocean depth on the Chile-Samoa path, the expression

$$C = (gd)^{1/2}$$

gives the mean depth as 15,312 feet.

As has been pointed out by Green (1946), however, the probable path is not necessarily the single great circle from the epicenter. The 22 May tsunami arrived at Samoa well ahead of the computed estimated time of arrival.

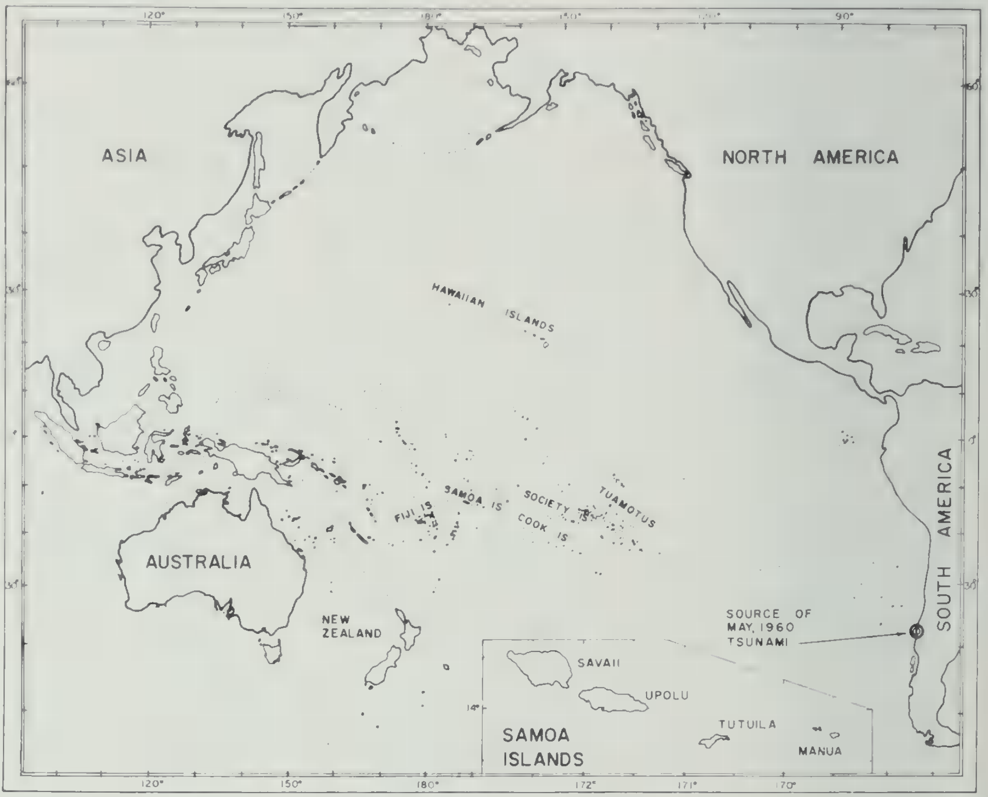


FIG. 1. Map of Pacific Area.

The tsunami was not observed at Rarotonga in the Cook Islands until about the time it was recorded in Samoa, although the first arrival should have been expected in the Cook Islands nearly two hours earlier than at Samoa.

TSUNAMI IN UPOLU

The first news of an impending tsunami reached Apia Observatory, Upolu, Western Samoa (fig. 5) at approximately 2100 hours local time on 22 May. It was learned that Honolulu broadcasting stations were reporting that a large earthquake

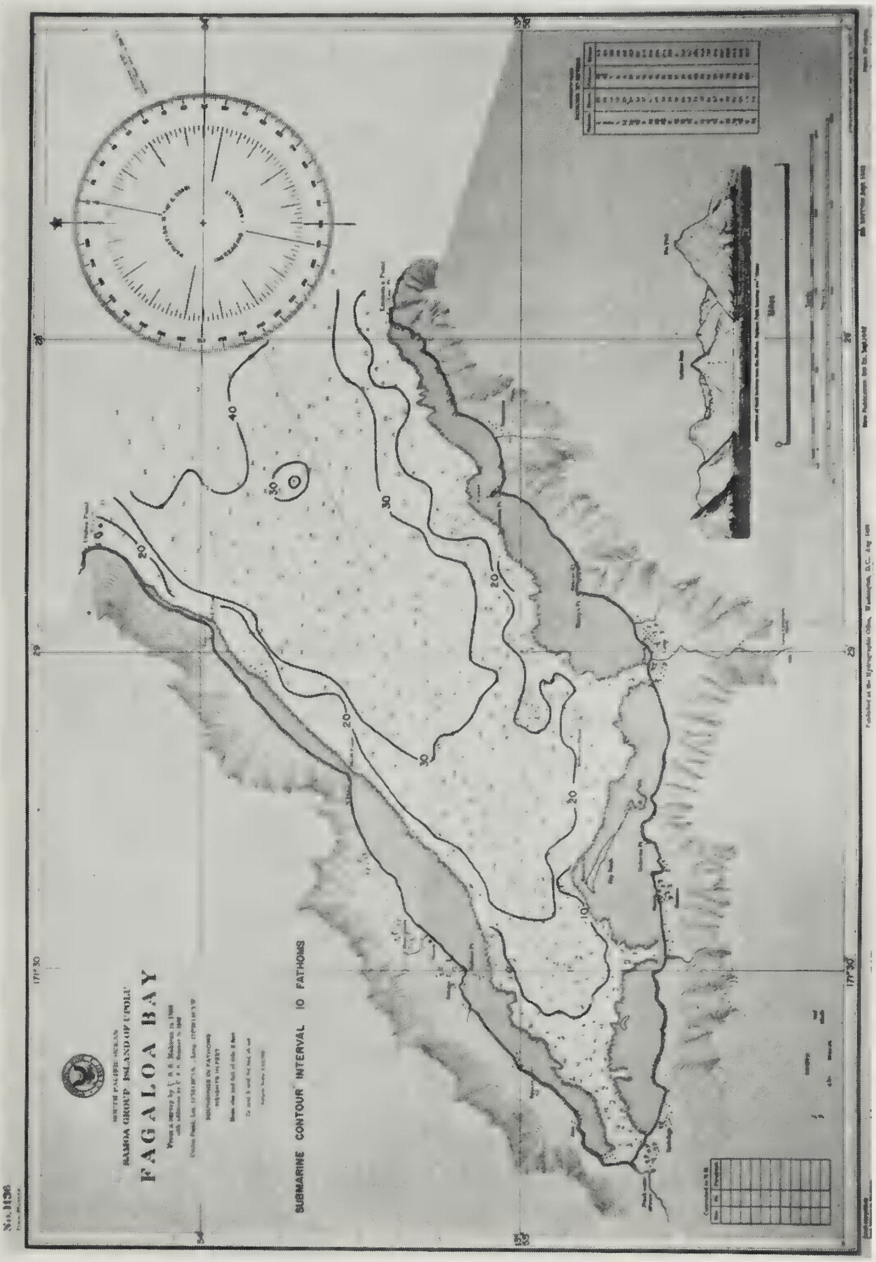


FIG. 2. Map of Fagaloa Bay, Upolu. (From U. S. Naval Hydrographic Office Chart 1136.)

in Chile had generated a tidal wave. On tuning in to Honolulu, reports were received of the preparations being made in case the tsunami reached the Hawaiian group.

Apia Radio (ZMB) was then contacted; it advised that no tidal wave alerts had been received up to that time.

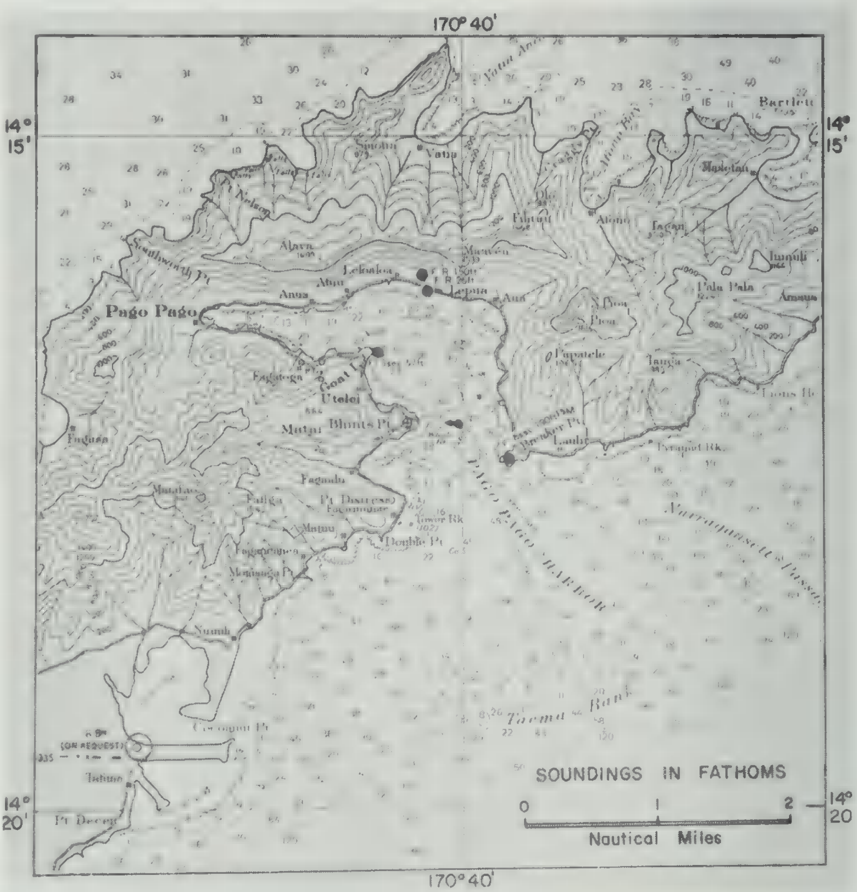


FIG. 3. Map of Pago Pago Harbor and Environs, Tutuila. (From U. S. Coast and Geodetic Survey Chart 4109.)

At this stage, the Director of Broadcasting, who was at Apia Observatory, suggested that the local broadcasting station (2AP) remain on the air. In view of the apparent imminence of the tidal wave, it was suggested that a preliminary warning be issued, advising people in coastal areas to be prepared to move to higher ground. Special emphasis was to be placed on warning the Aleipata and Fagaloa Bay districts, in view of their location and previous experiences during tsunamis.

At 2130 hours Apia Radio advised that an official warning (230447 Z) of Honolulu Magnetic Observatory (HMO) had just been received. This gave the tsunami's estimated time of arrival at Samoa as 2200 hours, and 2AP was advised to broadcast the preliminary warning as mentioned above. The Secretary to the Government was advised of the action that had been taken.

Rarotonga Radio in the Cook Islands was then queried as to whether tidal wave activity had been experienced there. The reply was negative. It was later found that the first, though not the most serious, wave did strike Samoa at about 2050 hours, but it seems not to have been observed. No reports of tidal wave activity in Samoa had come in by 2230 hours; at that time a further message from Rarotonga stated that tidal wave activity was in progress. It was erroneously assumed that this was the first arrival in Rarotonga, and 2AP was advised that the tsunami could now be expected at about 2330 hours. However, this was the second major wave, and the one responsible for damage at Aleipata and Fagaloa Bay at 2345 hours.

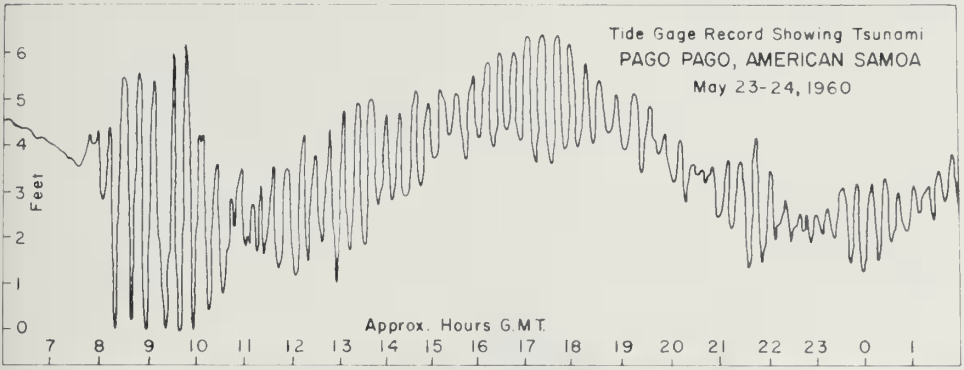


FIG. 4. Marigram From Pago Pago Harbor, Tutuila, Showing May 1960 Tsunami. (After Symons and Zetler, 1960).

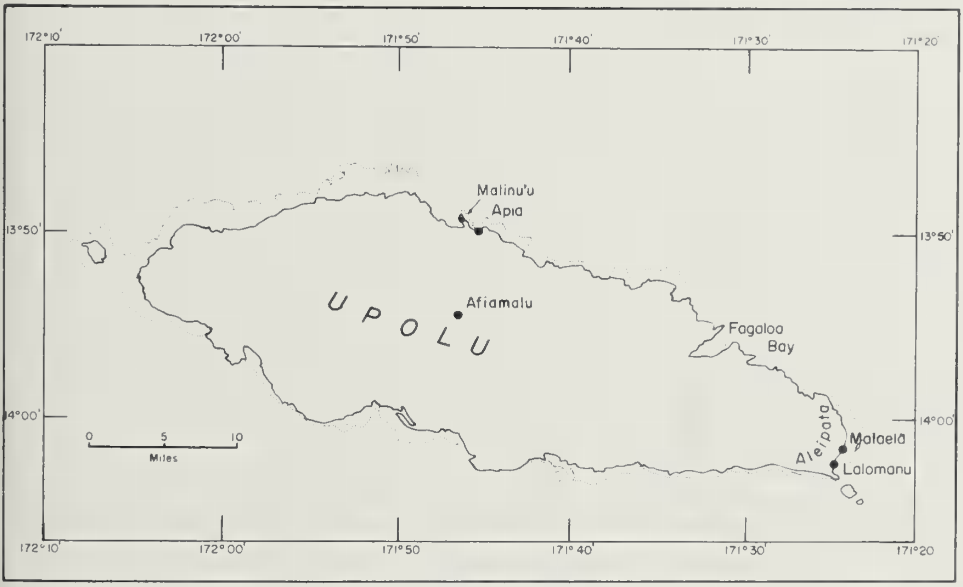
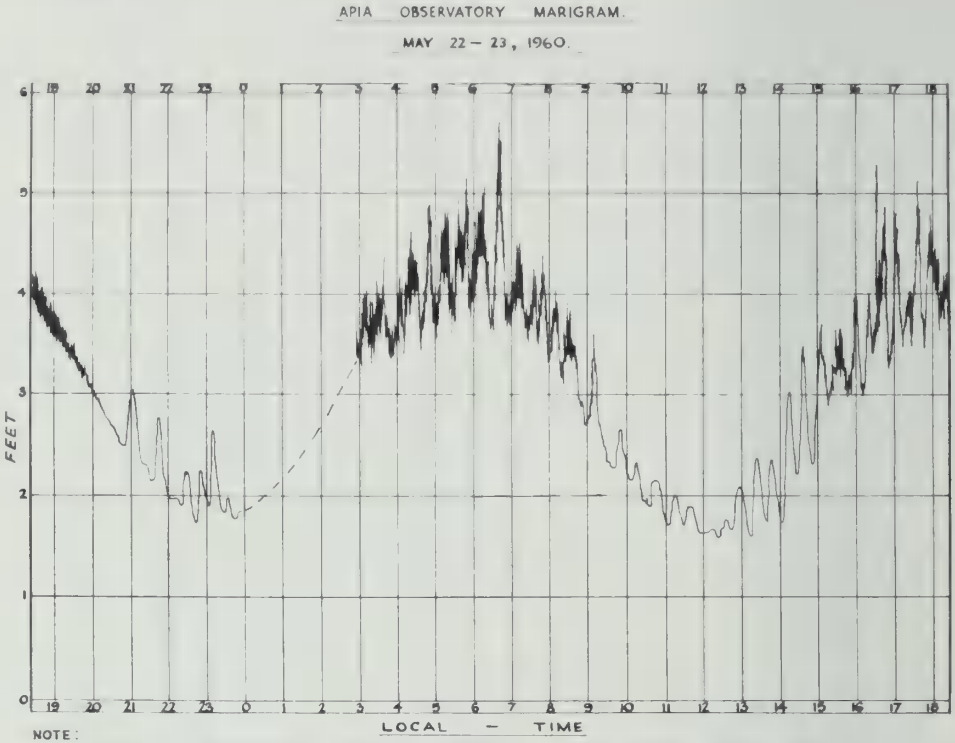


FIG. 5. Map of Upolu, Western Samoa.

At about midnight the customs wharf, Apia Harbor, was visited. The tsunami activity observed there was very prominent, displaying a wave period of about 8 minutes and a range of about 4 feet. The effects of the tsunami could also be observed at Mulinu'u, although, as could be expected, they were much less pronounced there, as a result of the sheltering effect of the reef at low tide. The Apia tide-gage records (fig. 6) show a wave period of about 20 minutes at this stage, and a range of about 1 foot.



NOTE:
① THIS IS A RECONSTRUCTION FROM THE ORIGINAL. THE DASHED TRACE INDICATES THAT SECTION OF THE ORIGINAL MARIGRAM MISSING AS A RESULT OF FAULTY EQUIPMENT.
② THE SHORT PERIOD ACTIVITY AT HIGH TIDE IS CAUSED BY SURF CROSSING THE REEF.

FIG. 6. Marigram From Apia Observatory, Upolu, Showing May 1960 Tsunami.

Shortly after 0130 hours, a further message was received from Rarotonga that stated that the wave had arrived at 2100 hours local time and caused considerable damage to small craft. No action was necessary.

At about 0230 hours, several members of the Observatory staff left Mulinu'u for Malaela and Fagaloa Bay. The party arrived at Lalomanu shortly before dawn, having stopped several times on the south coast of Upolu to observe the tsunami and to gather information where possible.

At Lalomanu, where the tide was approaching full, it was heard that at about 2345 hours the previous night a large wave had picked up two fishermen in canoes near the reef and washed them onto the beach by the road. At 2345 hours, the tide here would have been dead low, and the road in this area lies about 3 feet above high-water mark. In other words, this crest had an amplitude of about 6 feet. The

TABLE 1

TSUNAMI OF 23 MAY 1960 AT UPOLU

Locality	Time (GMT)	Range, ft	Period, min	First feature	Remarks
Observatory tide-gage record	0750	½	30	crest	First arrival.
Fagaloa Bay	0815±	6±	10±	—	Observed by Samoans.
Sataoa	0915±	8±	20	—	Three large waves at this time, second and third being largest; max. crest +5 ft. Report reliable. Reef offshore.
Fagaloa Bay	1045±	16±	10±	trough	Observed by Samoans. Major wave in Samoa. Subsequent crest caused minor damage to buildings; 44 gal drums of gasoline carried 80 yd inland. Probably correlation between this and similar wave in Rarotonga at approximately 0930 hr GMT; no indication of series of crests.
Lalomanu	1045±	6±	—	crest	Range refers to half amplitude; this wave appears to be the same as the crest at Fagaloa Bay, possibly preceded by trough, but no conclusive verification. Two fishermen in canoes ±1 mile from shore, but inside reef, swept ashore. One major wave only.
Poutasi	1100(?)	6–7±	5(?)	—	Report sketchy. Reef well offshore.
Apia Harbor	1100	4±	8±	—	Prominent continuous surge but no sinusoidal wave form observed; no damage at any stage.
Upolu south-coast beaches, e.g., Lepa	1430–1600	Approx. 4–6	5–6	—	Continuous short-period surges.
Malaela	1730	6±	4	—	Successive crests advancing and retreating across lagoon for about 1 mile, as long straight lines.
Fagaloa Bay	1930	4±	3	—	Sinusoidal waves coming up bay could be seen from Fagaloa saddle.

TABLE 1—(*Continued*)

Locality	Time (GMT)	Range, ft	Period, min	First feature	Remarks
Apia Harbor	2315	5		trough	Sea retreated in harbor and returned several minutes later. Eyewitness accounts not consistent. One wave only, but no sign on tide-gage record.
Observatory tide gage record	to 29 May				Tsunami can be identified up to this time; no indication of new onset corresponding to sea wave of 25 May; no reports of this second wave being observed in Samoa.

period is not known. It is possible that this wave was preceded by a trough, but this has not been verified.

At Malaela, as daylight approached and the tide became higher, it was seen that successive crests of the tsunami appeared inside the reef as lines, perhaps as long as a mile, that advanced across the lagoon and onto the road, and then receded in the same form. The reef in this region is inclined to the shoreline, its distance varying from 1 to 2 miles. The tsunami waves formed parallel to the reef and, hence, arrived at the shore at an angle. The period of this wave action was unusually short—about 4 minutes—and the range about 6 feet.

After this, the party left for Fagaloa Bay and arrived at about 0900 hours. The residents of Fagaloa Bay had heard the announcements on 2AP the previous night, and had also seen unusual tidal activity, starting at about 2115 hours, with an estimated range of about 6 feet and a period of approximately 10 minutes. They had, in accordance with 2AP's instructions, taken refuge on higher ground.

At about 2345 hours a great recession caused the sea to retreat beyond the reef, leaving the head of the bay free of water. A few minutes later (no reliable estimate can be given) the villagers heard the roar as the sea began its advance.

The crest that followed advanced 90 yards through the village, rising to a height of approximately 8 feet above the normal tide, which was on the ebb and approaching low water. The range between crest and trough maxima was therefore estimated at 14–15 feet.

This wave and the recession that followed was responsible for all the damage at Fagaloa Bay. It was obviously the same wave that had been seen at Lalomanu. In Fagaloa Bay the peak water level reached the roof of one of the native houses; it was reported that children had been sleeping here before the warning given by 2AP. Debris was scattered about the village, including 44-gallon drums of petrol from one of the two stores. Only one of these stores suffered apparent structural damage. No lives were lost.

Photographs that were taken of Fagaloa Bay from the Fagaloa saddle at about 0830 hours, 23 May, show the waves advancing up the bay. The range of these waves is about 4 feet, their period about 3 minutes.

On returning to the Observatory, inquiries were made as to why the tsunami warnings had not been received earlier, or, in the case of HMO's first advisory message, not received at all.

The reply from the Regional Communications Officer at Nandi, Fiji, stated that Apia had been deleted from the list of addressees for whom Nandi was automatically responsible. The only reason HMO's 230447 Z was received was that the duty supervisor at Nandi had noticed a reference to Samoa in the information on estimated tsunami arrival times, and had on his own initiative relayed the message to Apia.

This was the first intimation received that Apia had, in fact, been deleted from the list of stations to which Nandi would automatically reoriginate tsunami alerts. It was obvious that the matter needed clarification, since seismo dummies (the testing procedure for tsunami alerts) had been received in the normal way at Apia as recently as April and May, 1960. In addition, Apia furnishes seismic data and tide-gage information by cable to the U. S. Coast and Geodetic Survey, and data on tsunamis are sent to Scripps Institution of Oceanography, San Diego, Calif. It was apparent that Apia was cooperating to the fullest possible extent with these institutions.

A message was dispatched to Honolulu Magnetic Observatory, with an information copy to Nandi, requesting clarification of the system, and also requesting that Apia be reinstated on the warning list. The U. S. Coast and Geodetic Survey replied that it was prepared to do so, and this has since been done.

SECOND CHILEAN TSUNAMI

On the morning of 25 May, the Director of Broadcasting advised that Radio Australia's morning news had announced the occurrence of a second earthquake or series of earthquakes in Chile, again accompanied by tidal wave activity. The Observatory's Wood-Anderson seismograph had recorded no major earthquake the previous night. Benioff seismograph records, however, showed a distant earthquake at about 90 degrees distance.

The average velocity of the previous Chilean tsunami was about 500 mph, and it was clear that this second tsunami, if generated at the origin time of approximately 0830 hours GMT, would arrive at Samoa at approximately 2100 hours GMT; that is, 1000 hours local time, 25 May.

The Director of Broadcasting and the Secretary to the Government were advised of the situation, and 2AP announced that it was possible another tsunami would reach Samoa at about 1000 hours, if it had in fact been generated.

Pago Pago and Nandi were contacted; both stated that no warnings had been received.

Because there was so little concrete information available, 2AP was advised that the public should be warned to stay alert until 1300 hours local time.

At 1300 hours, information copies of HMO's initial warning and subsequent ETAs were relayed to Apia Radio by Nandi.

These messages confirmed the tsunami ETA for Samoa that had been calculated earlier, and it was apparent that the danger had passed for Samoa. The local broadcasting station, 2AP, was advised accordingly.

The Observatory tide-gage record was inspected, but no positive identification of the tsunami could be made because of oscillations from the first tsunami that were still in progress.

There were, however, no reports of renewed activity as a result of the second tsunami. It seemed certain that, if generated at all, it must have been much less prominent than the tsunami of 22 May.

TSUNAMI GENERATED BY FORESHOCK

It was reported (personal communication with Doak C. Cox) that a minor tsunami had been recorded at Hilo, Hawaii, some 33 hours before the main tsunami. This minor tsunami was supposedly generated by the first foreshock in Chile, at 1002 hours GMT on 21 May.

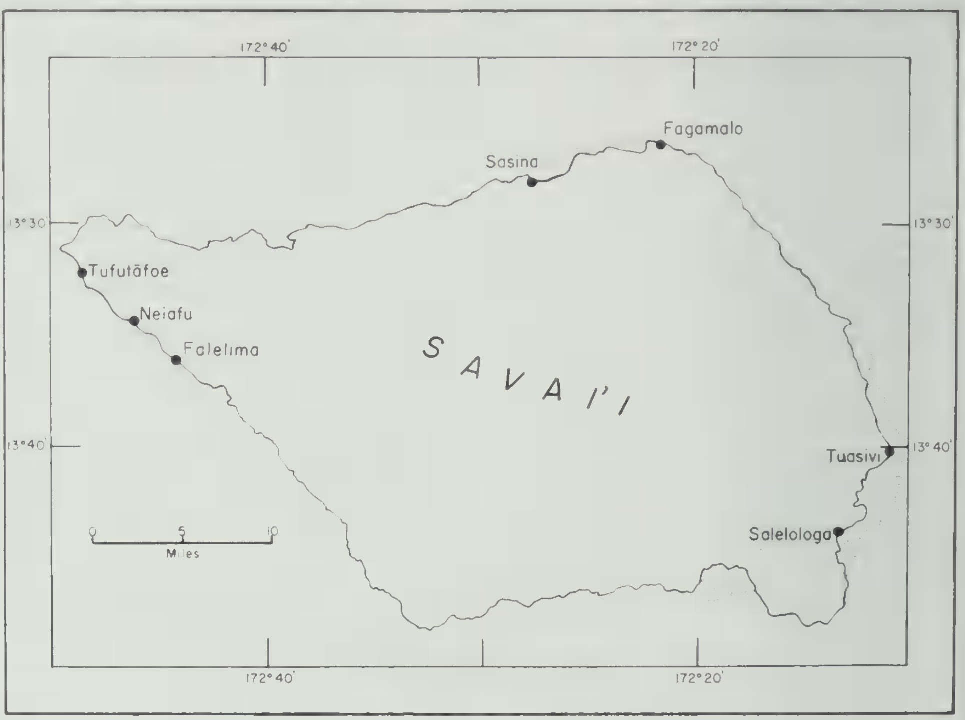


Fig. 7. Map of Savai'i, Western Samoa.

The Apia Observatory marigram showed a small-amplitude oscillation at approximately 1150 hours local time, and this motion was again apparent on the next low tide, with a period of about 20 minutes.

Float-well observations at the tide gage, however, confirmed the existence on the lagoon of an oscillation of period 15–20 minutes, which presumably resulted from a seiche existing on Apia Harbor.

It is not possible, therefore, to state conclusively that movement on the marigram at 1150 hours was tsunami-generated, although it appears more pronounced than is usually the case.

Tsunami in Savai’i

Information from Savai’i (fig. 7) is incomplete, due in part to the time that elapsed between the tsunami and the collection of information, and in part to the necessary use of an interpreter.

The tsunami seems to have been first observed at Falelima, on the northwest coast, at 2100 hours. The reef at the point of observation is within 2 chains of the shore.

At approximately 2345 hours, three large waves were observed with an estimated range of 8 or 9 feet (+5 to −4) and a period of about 30 minutes. These waves represented the most active phase observed at this location.

At Neiafu, one major crest was observed that attained a reported height of 7 to 8 feet. Times given are unreliable.

TABLE 2

Tsunami of 23 May 1960 at Savai’i

Locality	Time (GMT)	Range, ft	Period, min	Remarks
Falelima	0800±	8–9	30±	Three large waves. Reef, very close to shore.
Neiafu	—	10(?)	—	One large wave. Crest, maximum +7 to +8 ft.
Tufutafoe	0900±	10(?)	15±	Reef terminates 50 yd offshore. Two major crests, observed, maximum +6 to +7 ft.
Tuasivi	during night	4–5	short	Short period surges. Shallow lagoon screened by reef at about 500 yd.
Sasina	1600	5	30±	Waves over road at head of bay. Bay enclosed by reef.

At Tufutafoe, two large crests were observed at approximately 2200 hours that attained a height of 6 to 7 feet, with a period of about 15 minutes. In this locality the reef has been overridden by lava, which terminates about 50 yards from the shore.

The bay entrance at Sasina is screened by a reef. The tsunami was not observed until approximately 0500 on 23 May. The peak range here was about 5 feet, sufficiently high to come over the low-lying road at the head of the bay. The period was reported as about 30 minutes.

The tsunami was not observed at Fagamalo.

At Tuasivi the shore is completely screened by a reef about 500 yards out. The tsunami here manifested itself as short-period surges, with peak ranges estimated at 4–5 feet. This was the same sort of effect as that observed at the eastern end of Upolu, where the placement of the reef relative to the shoreline is similar.

It was impractical to obtain information at closely spaced intervals around the Savai'i coastline; nevertheless it is considered that the data obtained are representative. No outstanding topographical features similar to Fagaloa Bay, Upolu, or Pago Pago Harbor, Tutuila, are present where the effects of the tsunami could reasonably be expected to have been more pronounced.

TABLE 3

TSUNAMI OF 23 MAY 1960 AT TUTUILA

Locality	Time (GMT)	Range, ft	Period, min	First feature	Remarks
Pago Pago tide gage (Goat Island)	0735	$\frac{3}{4}$	15	crest	Crest amplitude of first arrival.
One half mile up bay from Goat Island	0900(?)	10–12	—	—	Crest maximum +6 to +7 ft; probably same crest as that on marigram at 0845.
Tafuna	0840	—	—	—	Not observed, but loud rumble for about 1 min.
One mile up bay from Goat Island	0815	8–10	20±	—	Series of five large waves identifiable on marigram.
Pago Pago village	—	15–16	20±	—	Village at head of bay; estimated $50,000 property damage.
Fagaalu	During night	4±	—	—	Debris on road. Fagaalu located immediately inside harbor entrance.
Pago Pago tide gage	To 29 May, 0100 hr	—	—	—	Tsunami identifiable to this time.

TSUNAMI IN TUTUILA

Three warnings from Honolulu Magnetic Observatory were received in American Samoa. The first was received at 1600 hours on 22 May, Samoan Standard Time (SST), and stated the earthquake origin time and epicenter. The second warning, received at 1811 hours SST, stated that a possible damaging wave would arrive at Hawaii at approximately 2400 hours Hawaiian Standard Time.

The third warning, received at 2008 SST, gave the estimated wave arrival time at Tutuila as 2200 hours SST. On the final warning, public gathering places were closed and people advised to return to their homes. A very few evacuated to higher ground.

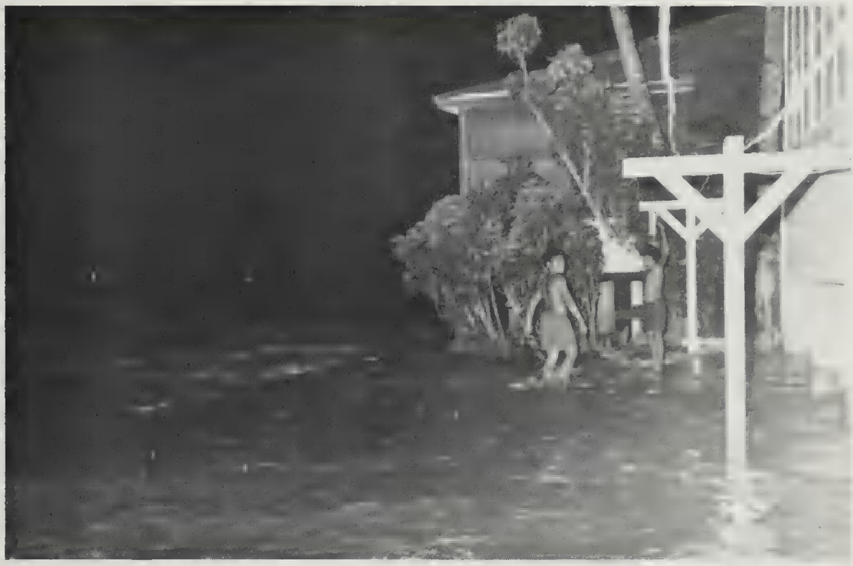


FIG. 8. Flooding by Third Wave of Tsunami at Rainmaker Hotel Annex, Pago Pago, Tutuila, About 2300 Hours, 22 May 1960. (Photo by Frank Morse.)

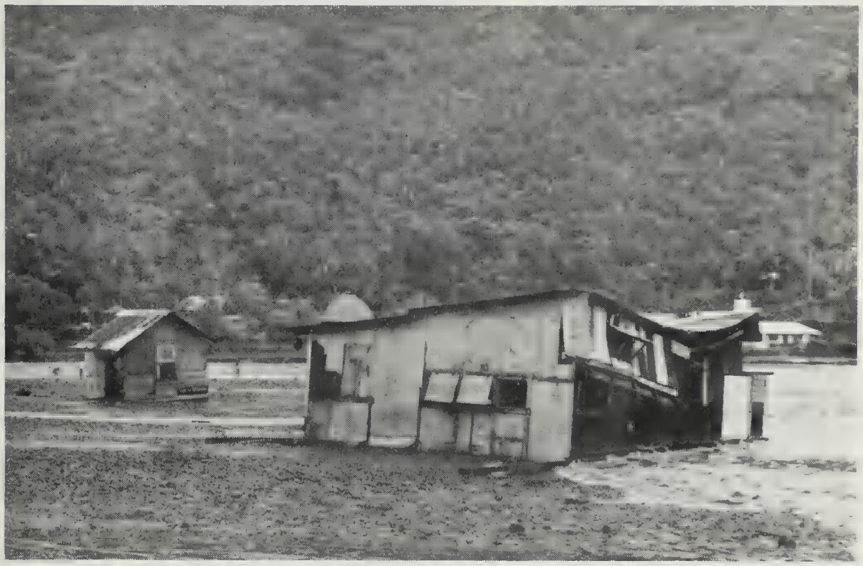


FIG. 9. House Washed by Tsunami Into Pago Pago Bay, Tutuila. (Photo by Frank Morse at time of trough about 1000 hours, 23 May.)

The Pago Pago marigram shows the first wave as a crest arriving at approximately 2035 hours (figure 4). The subsequent recession was the first stage at which visual observations took place. Observers noted that there were approximately 10 wave crests and troughs, of which the third and fifth were considered to be the largest. The wave period was estimated as approximately 20 minutes.

At the Administration boatshed, some 800 yards farther up the bay from the tide gage, the peak amplitude was 6–7 feet above the normal tide, which at that time was on the ebb and approaching low water. The wave reaching this peak was observed shortly before 2200 hours, and can probably be correlated with the crest recorded on the marigram at 2145 hours. The subsequent trough attained a maximum of approximately 4–5 feet, giving a range of approximately 10–12 feet.

A half mile farther up the bay from the boatshed, the wave action was observed by Mr. Morse. He reports that five waves came over the top of the retaining wall behind his house, and of these the fourth was the largest. This group of five large waves is readily identifiable on the marigram. Maximum range at this location was estimated at 8–10 feet, crest to trough. A photograph taken at the Rainmaker Hotel Annex in this area is shown as figure 8.

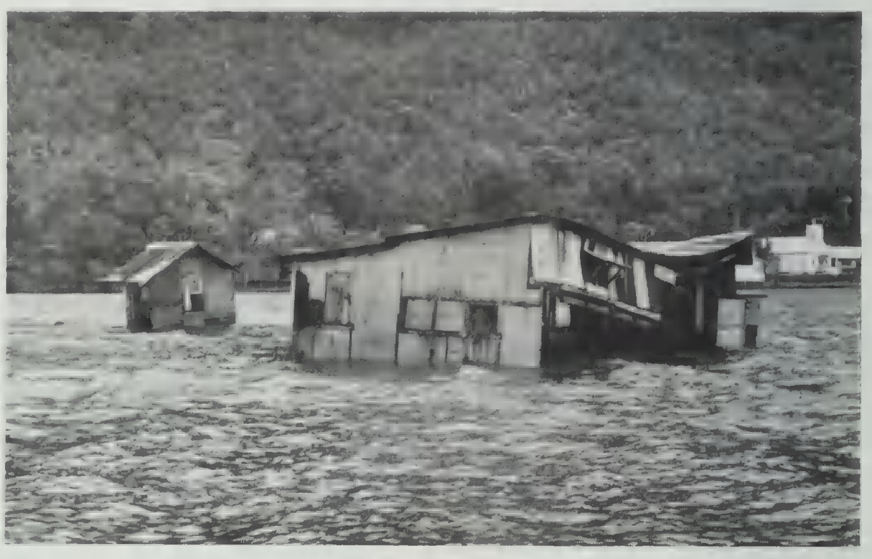


FIG. 10. Same House as in figure 9, at Time of Crest, 5–10 Minutes After figure 9. (Photo by Frank Morse.)

At Tafuna airport, Mr. Elmer Wilson reported that a loud rumble was heard at about 2140 hours, the duration being approximately 1 minute. It is considered that this was a manifestation of the crest observed at the boatshed.

No tidal disturbance was noticed at Tafuna, which is screened by an offshore reef, despite the fact that observers equipped with spotlights were keeping a watch for any unusual activity.

At Pago Pago village, which is located at the extreme west end of the harbor, the tsunami reached its greatest proportions in Samoa. The peak range here was 15.5 feet (+9.5 to −6.0), and damage estimated at $50,000 resulted. Mr. E. Brunton, of the Survey Department, made the following analysis of the damage:

"One house was lifted and moved about 10 feet inland and another was washed into the bay by the outgoing wave. A school, substantially constructed on concrete piers, was rotated about a foot with consequent springing of nearly all structural members." Figures 9 and 10 are photographs of this area, taken at approximately 1000 hours on 23 May.

TABLE 4

Benioff Seismic Data, Afiamalu, Western Samoa

1960	Phase	Component	Time (GMT)			z		Z		N	
			Hr	Min	Sec	Amplitude, micron	Period, sec	Amplitude, micron	Period, sec	Amplitude, micron	Period, sec
5/21	eiP	zZ	10	15	52	4	3	25±	10±	—	(dil.)
	iPP	Z	—	18	57	—	—	10	10	—	(dil.)
	e	N	—	19.5	—	—	—	—	—	8	12
	eS	ZN	—	26	10	—	—	44	16	100±	24±
	eSS	N	—	31.8	—	—	—	—	—	—	—
	ei	Z	—	32.3	—	—	—	205	20	—	—
	rLq	ZN	—	39.1	—	—	—	62	23	—	—
	eLr	ZN	—	43.5	—	—	—	1030	26	630	25
	M	ZN	—	46.5	—	—	—	—	—	986	19
5/22	iP	Z	10	43	41	—	—	5	6	—	—
	(PP)	Z	—	47	04	—	—	6	8	—	—
	eS	N	—	54.0	—	—	—	2	10	—	—
	(SS)	ZN	—	57.3	—	—	—	56±	28±	70	21
5/22	iP	zZ	10	45	51	3	3	12	5	—	—
	iPP	Z	—	49	06	—	—	6	7	—	—
	eS	N	—	56.0	—	—	—	—	—	60	24
	eSS	N	11	01.5	—	—	—	54±	20	—	—
	i	Z	—	05	20	—	—	18±	24±	—	—
	eLq	ZN	—	09.0	—	—	—	27	20	32	22
	eLr	ZN	—	13.3	—	—	—	423	26	140	24
	M	Z	—	15.4	—	—	—	564	20	—	—
5/22	iP	zZ	19	08	54	1	2	25	8	—	—
	ePP	Z	—	12	08	—	—	4	6	—	—
	ePPP	Z	—	14	20	—	—	10	12	—	—
	i	Z	—	19	11	—	—	10	13	—	—
	iS	N	—	—	23	—	—	—	—	120	24
	i	Z	—	—	38	—	—	92±	25±	—	—
	e(SS)	N	—	21	11	—	—	—	—	—	—
5/22	iP	zZ	19	23	39	—	—	8	6	—	—
	iPP	N	—	27	03	—	—	—	—	—	—
	PPP	N	—	30	19	—	—	—	—	—	—
	S	N	—	34	25	—	—	—	—	180±	22±
	iSS	N	—	42	04	—	—	—	—	896±	20
	SSS	N	—	47.0	—	—	—	—	—	441	14
	LM	N	—	51.4	—	—	—	—	—	3580±	26
5/22	iP	zZ	19	24	05	0.1	1	12	5	—	—
	iPP	N	—	28	02	—	—	—	—	14	4
	PPP	N	—	30	19	—	—	—	—	30±	9±
	S	N	—	35	25	—	—	—	—	1720±	24
	SS	N	—	43.4	—	—	—	—	—	999±	20
	SSS	N	—	49.0	—	—	—	—	—	388±	10±
	(Lq)	N	—	54.4	—	—	—	—	—	2948±	40±
	(Lr)	N	—	55.7	—	—	—	—	—	3482±	20
5/25	iP	zZ	08	47	20	0.2	1.5	4	7	—	—
	eS	ZN	—	57	48	—	—	17	20	—	—
	eSS	ZN	09	02	37	—	—	21	22	—	—
	e(L)	N	—	09.8	—	—	—	51	30	—	—
	eL	ZN	—	12.7	—	—	—	—	—	—	—

At Fagaalu, located immediately inside the harbor entrance, the sea rose no more than 2.5 feet. A small channel runs through the reef off Fagaalu.

No reports of activity could be obtained from coastal villages, and it seems evident that Pago Pago Harbor was the only location where the tsunami was observed. It appears that the effect around the Tutuila coast was much less pronounced than it was on the coasts of Upolu and Savai'i, although rough water was observed inside the lagoon at the extreme eastern end of Tutuila on the day following arrival of the tsunami.

TABLE 5

PREVIOUS TSUNAMIS IN SAMOA[a]

Date	Source	First arrival (GMT)
1 May 1917	Kermadec Islands	note[b]
25 June 1917	Samoa Islands	0555
7 September 1918	Kurile Islands	0223(9–8–18)
30 April 1919	Tonga Islands	0812
20 September 1920	New Hebrides Islands	1904[a]
11 November 1922	Chile	1836
3 February 1923	Hawaiian Islands	0142(2–4–23)
17 June 1928	Mexico	1550(?)
3 June 1932	Mexico	2145
2 March 1933	Japan	—
7 December 1944	Japan	1100(?)
1 April 1946	Aleutian Islands	2143
1 April 1946	Californian Reflection	0208(4–2–46)
4 November 1952	Aleutian Islands	0235(11–5–52)
9 March 1957	Aleutian Islands	2320
6 November 1958	Kurile Islands	1255(?)(11–7–58)

[a] See Heck, 1947.
[b] Apia marigram not available.

TSUNAMI IN THE COOK ISLANDS

The tsunami was of little consequence in the Cook Islands except in harbors like Avarua and Avatiu on Rarotonga that represent reef openings with shelving bottom. No information was received from atolls of the Northern Cook group, such as Penrhyn and Suwarrow; but it is likely that energy penetrating reef passages would be dissipated in the large and deep lagoons.

According to Mr. G. Russell, Meteorological Officer at Rarotonga (in an informal communication), the first oscillation of the tsunami was observed at about 0745 hours GMT on 23 May; the amplitude increased to a peak at about 0930 hours; then noticeably decreased for at least 50 minutes. Later it built up again quickly to a second peak at about 1100 hours. There was some damage to yachts in the harbor during this second peak. The period of the oscillation was close to 4 minutes and the maximum height was estimated at 5 feet. Fortunately the arrival of the tsunami coincided with low tide, when in fact the sea level was below the level of the coral reefs.

CONCLUSION

In the Samoa Islands, the tsunami of 22 May was most pronounced at the heads of Fagaloa Bay and Pago Pago Harbor, where the maximum ranges were 15–16 feet. In the Cook Islands, the maximum ranges were at Avarua and Avatiu harbors, where they amounted to about 5 feet. A tsunami even of these proportions constitutes a considerable menace to human life and emphasizes the need for the maintenance of rapid communications in the sea-wave warning network. Reception of warnings well in advance of suspected sea-wave activity will also permit the implementation of observational programs of greater accuracy than have been possible in the past.

ACKNOWLEDGMENT

The author is indebted to F. Uhrle and E. Brunton, of the American Samoa Administration, for their assistance in supplying information on the tsunami effects in Tutuila and to F. Morse, for supplying photographs of the tsunami in that area; to J. Franklin and C. Capper, of Apia, for their help in recording effects in Upolu and Savai'i; and to G. F. Russell, of Rarotonga, for supplying information relating to the effects on that island. The author wishes to thank Doak C. Cox, of the Hawaii Institute of Geophysics, for helpful discussion and advice.

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THE TSUNAMI OF 22 MAY 1960 IN FRENCH POLYNESIA

By Martin J. Vitousek

ABSTRACT

Except for the Marquesas Islands, the islands of French Oceania are relatively safe from tsunamis because of well-developed reefs, inner lagoons, and steep offshore slopes, hence the Chilean tsunami of 22–23 May 1960 was not well developed. Detailed data are given for Tahiti. The greatest runup height was 3.4 meters above low water, the average was 1.7 meters. Runup of 1 meter was observed in the Leeward Islands. In the Austral Islands the highest wave reached 1.8 meters. The Tuamotu Archipelago suffered water level changes of about 1 meter. In the Marquesas Islands runups of about 3 meters were observed.

No human casualties were reported from French Polynesia and damage was slight.

Introduction

The tsunami associated with the earthquake of 1911 hours, GCT, Sunday, 22 May 1960, centered in southern Chile (see fig. 1 of the article by Keys starting on page 1211 of this number) struck the islands of French Polynesia (fig. 1) just after dark on the evening of the same day. There were no human casualties reported and, in general, property damage was minor. A warning propagated by the local broadcast radio was responsible to some extent for the prevention of casualties.

The information contained in this report was gathered by the author while on vacation in French Polynesia during the latter part of 1960. An extensive survey of the runup heights of the tsunami was made on the island of Tahiti, and spot checks were made on several of the other islands. All of the information on runup heights was obtained from personal interviews, as physical evidence such as driftwood deposits, etc., had long since disappeared by the time the survey was made.

Society Islands

Submarine and coastal topography: Although published charts lack sufficient offshore soundings for good definition of the topography, those available suggest that Tahiti is rather steep offshore with a submarine slope of about 30 degrees. Most of the island is surrounded by a barrier reef, inside which there are lagoons of considerable depth. The small tidal range (25 cm) allows the barrier reefs to build up to a level slightly above mean sea level. There are a few passes through the barrier reefs connecting the deep lagoons to the sea.

The leeward islands of Moorea, Raiatea, and Huahine are almost completely surrounded by outer barrier reefs and deep inner lagoons. The ocean bottom drops off very rapidly beyond the outer reefs at nearly 45 degrees down to the 2,000-meter isobath.

The lagoon beaches are, in general, very low. Normally, shallow coral shelves extend seaward from the beaches for distances between 10 and 100 meters. Beyond, the bottom generally drops off suddenly to a depth of 20 to 50 meters. The lagoon basin extends to a zone near the barrier reef where the bottom gradually rises and is usually studded with coral heads. As mentioned earlier, the barrier reef is usually at or slightly above sea level.

Where there is no barrier reef, the beaches fronting on the ocean, for example along the north shore of Tahiti, are composed mostly of black sand or lava shingle. The majority of these beaches have been built up to a height of over 2 meters by the action of heavy surf.

Tahiti tide-gage record: The tide-gage record of Matavai Bay, Tahiti, is reproduced in figure 2. There are several features of note. The first evidence of the tsunami was a slight lowering of the sea level beginning at 1925 local time (150th Meridian time) followed by a large crest at about 1955. The highest level occurred at 2148 hours, after which the tsunami became a decaying train of low-amplitude waves. The first 2 hours of activity were dominated by five large oscillations lasting from 20 to 24 minutes, after which such oscillations ceased abruptly. Superimposed on these oscillations (starting at about 1945 coincident with the first major rise) was another series of oscillations of small amplitude and high frequency. They began with a period of about 10 minutes and gradually changed to a lower amplitude and shorter

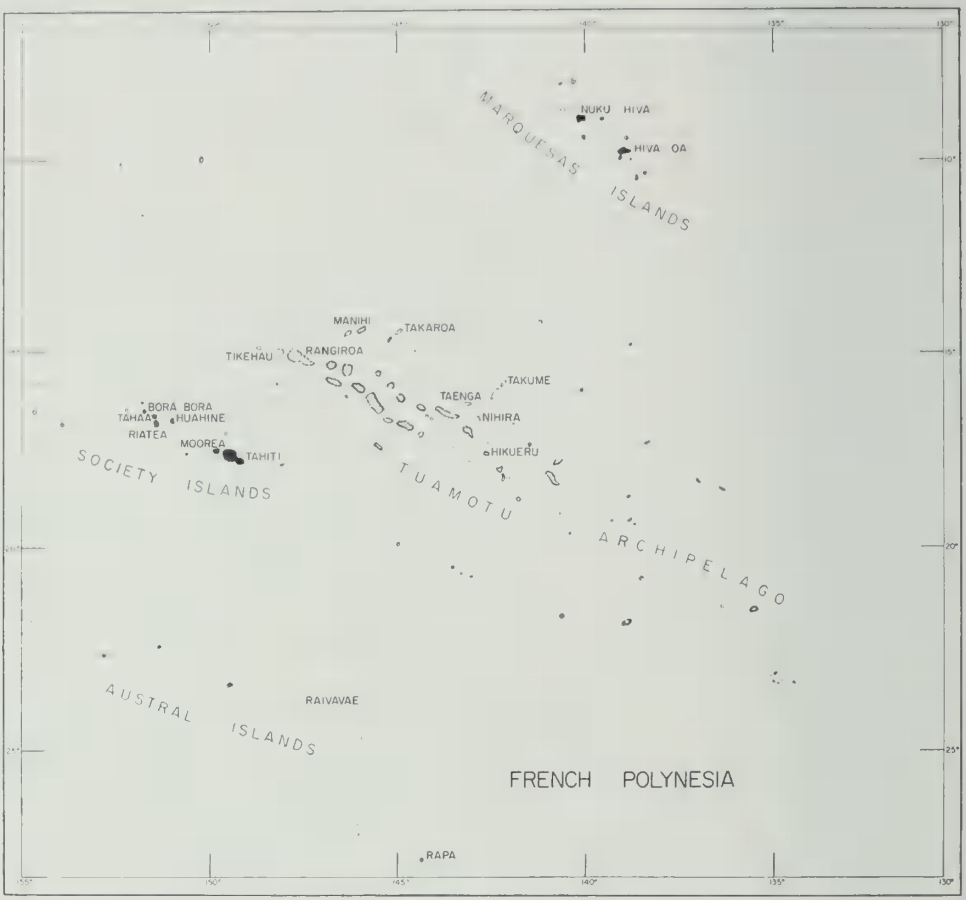

Fig. 1. Map of French Polynesia Showing the Location of the Islands Mentioned in the Text.

period of 7 to 8 minutes. The record of this train of waves can be seen many hours after the start of the disturbance. At about 2120 hours, a still higher frequency oscillation, with a period of 3 to 4 minutes, began. Apparently, the highest level reached by the water, at 2148 hours, was a result of the arrival of these short-period waves. This highest frequency also continued for many hours after the initial disturbance. The sudden beginning of waves of 3- to 4-minute periods, $1\frac{1}{2}$ to $2\frac{1}{2}$ hours after the initial wave, can be seen in the tide-gage records of San Diego, Johnston Island, Christmas Island, Honolulu, San Pedro, and San Christobal (Galapagos Islands) as reproduced by Symons and Zetler (1960).

It is difficult to determine which disturbances were caused by local resonance and which were part of the tsunami. Most witnesses interviewed in Tahiti stated that the highest wave occurred near 2200 hours, suggesting that the sharp peak caused by the short-period oscillation occurred all around Tahiti. However, the general opinion of those on the east end of the island was that the highest peak was definitely after 2200 hours, despite the fact that this end is closer to the coast of Chile.

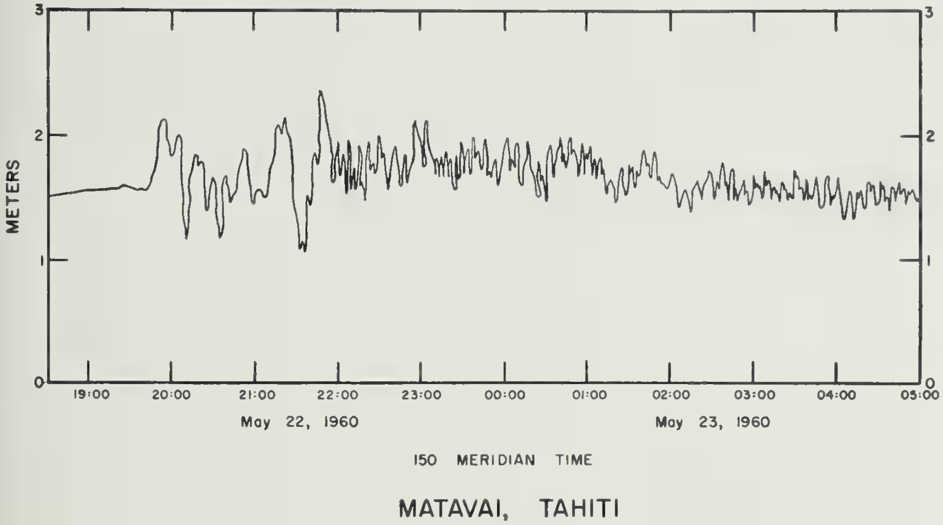

FIG. 2. Marigram for the Tide Station at Matavai, Tahiti, Traced From a Photocopy of the Original.

Wave runup on Tahiti: Because of the steep offshore slope, a tsunami does not receive much enhancement when impinging on the island. Furthermore, the lagoons that surround most of the island act as buffer reservoirs, reducing the effect of passing tsunami waves to a gentle rise and fall of the lagoon level. Because the restriction on outflow through the passes is more effective than that on inflow over the reef as well as through the passes, the drop in water level in the lagoons during a tsunami is much smaller than the rise. In the areas near the passes, the current attains considerable velocity.

Because the mean tide range is small (25 cm) and the shores are protected from storm waves by the barrier reefs, those living along the shore tend to build their dwellings on very low ground. A rise in water level in the lagoon of less than a meter above high tide is sufficient to inundate the floors of many of the huts.

The runup survey was made several months after the tsunami and after physical evidence of the inundation, such as deposits of debris and plant damage, had disappeared. Thus all measurements were based on limits of inundation observed by residents.

In general, the Tahitians are very aware of their natural surroundings and hence make excellent informants. Each interviewed was asked to indicate the highest point reached by the water. If stairs or a ladder were involved, they were also asked which steps were wet and which were dry. The time of highest water was requested as well. As few residents owned time pieces, the times given were not always precise. However, as the wave struck Sunday night, many could relate the time to local church services whose times were known.

Once the highest point reached by the water was found, its elevation above sea level was determined by sighting on a steel tape against the horizon. All measurements were then reduced to low water.

The results of this survey are shown in figure 3. The greatest height measured was 3.4 meters. Certain measurements, which are underlined, were considered more precise than others. All measurements were consistent except the one at Maraa. This unusual height could be explained by its proximity to a point of land. The average height of inundation for Tahiti was 1.7 meters. As might be expected, wave runup was highest along the north shore of Tahiti, where the coastline is exposed directly to the open sea.

There was no loss of human life in French Oceania attributable to the tsunami. Two or more huts were completely destroyed, and many huts and larger buildings were flooded. The Faratea hotel and restaurant was flooded, and an outside bar was destroyed. The bartender received warning of the approach of the wave over the local radio station at 1955 hours and had cleared the outside bar of its occupants just before it was destroyed at 2005, evidently by the first wave.

Effects on Leeward Islands: On Moorea, the water rose about 1 meter in Paopao Bay, flooding the Aimeo hotel and several huts and stores around the bay.

On Huahine, the water covered the wharf and ran inland, flooding some huts and buildings, but, in general, no serious damage was done. The height was again just over 1 meter.

The reports from Raiatea were similar to those from Huahine.

The Austral Islands

The author was not able to visit the Austral Islands. Although there is a tide gage at Rapa, it was not in operation during the tsunami, as the observer had previously met with a serious accident. The maximum wave height reported at Rapa was 1.5 meters. On Raivavae, the highest wave reached 1.8 meters. The wharf at Rairua was damaged.

The Tuamotus

The Tuamotu Archipelago consists mainly of coral atolls. The ocean bottom slopes off at 45 degrees or more near the reef, becoming more gradual at a depth of about 1,000 meters. The fall-off of the bottom is so great near the reef that it is generally impossible to anchor a ship offshore. This steep submarine topography is not effective in amplifying the wave height of tsunamis.

A general characteristic of these atolls is the presence of a steep high beach fronting the ocean. This high beach is lacking only when there is no land at all between reef and lagoon or, in rare cases, where the shore is a great distance from the outer reef. Normally, the shore is only 10 to 50 meters from the outer reef, so that storm waves strike the beach with great force, building up characteristic ramparts of coral rubble and sand, which protect the inner parts of the island from inundation during moderate storms. These ramparts are generally 3 to 5 meters above sea level.

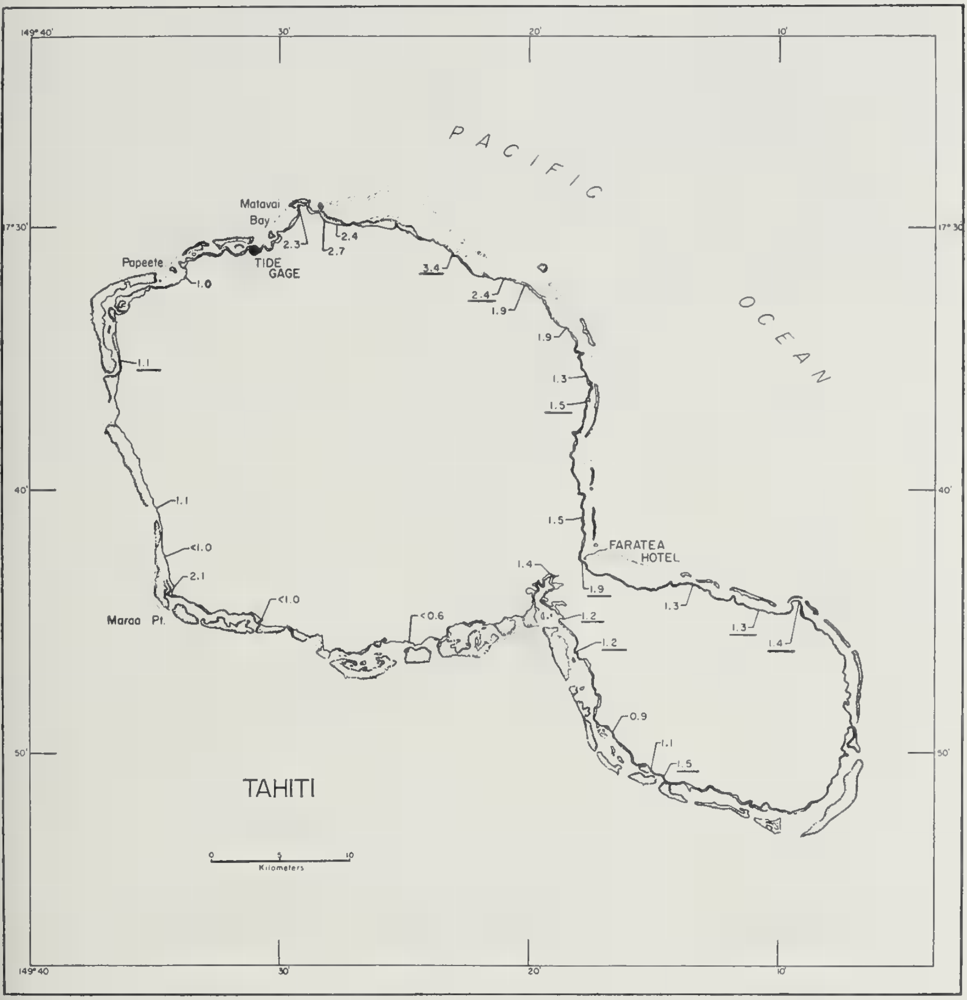

FIG. 3. Map of the Island of Tahiti, Showing Location of Places Mentioned in the Text and Runup Heights in Meters During the Tsunami of 22 May 1960. Heights underlined are considered more precise than the rest.

Some of the atolls have one or more deep but narrow passes connecting the lagoon with the ocean. Most of the atolls have several shallow water connections between ocean and lagoon, which, in some cases, are very extensive. A few of the atolls are completely closed with no connection between lagoon and ocean.

The villages are usually built on the lagoon side of the land strip, near the deep-water passes if they exist. Such locations are convenient as far as communication with the ocean is concerned and yet are protected from storm waves by the boulder ramparts and the widths of the islets. Thus the villages are nearly invulnerable to tsunamis, for the large deep lagoons offer the same buffer action as do the lagoons surrounding the high islands. The impinging waves of the tsunami do not fill or empty the lagoon more than a few tens of centimeters in depth.

The greatest change of level recorded in the Tuamotus was a recession of 1.8 meters at the main village on Takaroa. It may be remarked, however, that Takaroa is unusual among atolls, in that the deep part of the lagoon is distant from the land at the village and is connected to the sea by a long narrow channel that has a sharp turn as well as relatively shallow depths at the inner end. Thus, the water level at the village, which is close to the sea end of the pass, is more nearly that of the ocean than that of the lagoon.

On the other islands checked, Manihi, Rangiroa, Nihiru, Taenga, Takume, and Hikueru, the natives reported water-level changes of less than 1 meter. Most of the population was unaware of the passage of the tsunami, as it occurred at night.

Marquesas Islands

The Marquesas Islands present a departure from the bottom configuration of the islands previously discussed. There are few outer reefs, and the bottom slope is more gradual. From the few soundings available, the offshore slope is generally under 10 degrees and usually near 5 degrees. Large deep bays with gradually rising bottoms cause the waves of the tsunami to build up to heights several times their deep-ocean amplitude.

The Marquesas Islands generally present to the sea a coastline of high cliffs broken occasionally by deep bays with steep sides but flat slopes at their heads, running into valleys. The villages are mostly situated on the lowlands at the heads of the bays and are consequently very vulnerable to tsunamis. Indeed, in the history of the islands there are recorded many devastating tsunamis (Danielsson, 1957).

As the author did not visit the Marquesas Islands, an unpublished report by Rockne H. Johnson (1961) is reproduced here in its entirety.

"The writer of this report made a sailing cruise through the Marquesas Islands during the month of July, 1960. The information (concerning the tsunami of May, 1960) was received in both the English and Marquesan languages, the latter being necessarily limited in detail. Values given for the extent of both vertical and horizontal inundation represent visual estimates only and were not established by measurement instruments.

"Nuku Hiva

"Taio Hae: At McKittrick's store, directly at the head of the bay, water entered the front yard, an estimated 3 meters above sea level.

"Haka Ui: At the canoe landing, at the eastern side of the bay, water rose about

1.5 meters above ground level according to a point designated on the cliff face by an informant. This is estimated as 3 meters above sea level.

"Hiva Oa

"Hana Menu: This bay is uninhabited and there were no indications of unusual inundation as of 10 July 1960. It is on the sheltered side of the island.

"Taa Huku: At the point, under the lighthouse, observers estimated the height reached as high as 9 meters. There was some local speculation as to whether this represented solid water or spray. The sea nearly always breaks heavily on this point. Inundation at the head of the bay was much in evidence July 12, penetration into this low area being on the order of 200 meters. The shore line was cut back about 15 meters at the northeast corner and the trial descending the cliff at this point was removed to a height about 4.5 meters above sea level.

"Atuona: Buildings near the shore were destroyed. These included the jail, the radio station and a church. Penetration of inundating waters was about 200 meters inland. The only reported loss of life was to a horse tethered to a coconut palm in the inundated area.

TABLE 1

Readings From Tide Gage at Taiohae, Nuku Hiva

Time	Wave	Meters above datum
2000	—	1.95[a]
2040	1st	1.70
2110	2nd	1.40
2125	3rd	2.09
2150	4th	1.29
2205	5th	1.57

[a] Meters below datum. The initial drop in water level preceding the inundation.

"Fatu Hiva

"Hana Vave: Inundation was not reported by the inhabitants. This bay is on the sheltered side of the island."

The meterological observer at Atuona (Hiva Oa) reported that the first wave struck there at about 2030 hours and was followed by three other major waves. The last and largest was reported by him to be about 4 meters high. The meterological observatory was destroyed by this last wave, and if a fifth existed the observer did not see it as he was busy salvaging his equipment.

Although damaged so that the record was not reproducible, the tide gage at Taiohae, Nuku Hiva, which is 130 km northwest of Atuona, yielded information as reported by the French Navy (table 1). There may have been a change of datum between the first withdrawal and the first peak.

Summary and Conclusions

Except for the Marquesas Islands, the islands of French Oceania are relatively safe from tsunamis because of their generally well-developed reefs, inner lagoons, and steep offshore slopes. However, because of the small tidal range, the population tends to live on very low ground particularly susceptible to inundation. Along the north shore of Tahiti, where outer reefs are poorly developed or nonexistent, and at similar isolated locations on some of the other islands, there is considerable danger of serious inundation. The Marquesas Islands are particularly susceptible to damaging inundation in their deep flat-floored bays where conditions favoring wave buildup exist.

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FURTHER OBSERVATIONS OF GEOLOGIC AND GEOMORPHIC CHANGES RESULTING FROM THE CATASTROPHIC EARTHQUAKE OF MAY 1960, IN CHILE

By Wolfgang Weischet

(Translated by R. Von Huene)

ABSTRACT

A geomorphic study of the region in which the earthquake occurred, made after the earthquakes is compared with a similar study made before the earthquakes. Evidence is presented to show changes in land level. Discussion of the effects of the tsunami as it affected geomorphic and geologic processes is presented. Landslides are listed and analysed. Distribution of intensity is discussed.

Introduction

In May 1960, when southern middle Chile[1] was subjected to the great earthquake, I had just spent one year at the Universidad Austral de Chile in Valdivia as Director of the Geographic Institute. During this time and during a previous residence of one year in 1956, I had completed a series of geomorphic studies in the "little south," and was therefore fortunate enough to have sketches and photographs for many parts of the area prior to the catastrophic changes which occurred. Generous technical and financial support from the abovementioned university and from the German Research Association made it possible for me to study thoroughly the geological-geomorphic and the cultural changes associated with or following the earthquake in the part of Chile lying between 38° and 43° south latitude. A preliminary report (Ref. 2) and two special publications (Refs. 3 and 4) covering the studies completed by November 1960 have been issued.

Regional Distribution of Macroseismic Effects of the Earthquake of 22 May 1960, and Epicentral Location

The U. S. Coast and Geodetic Survey locates the epicenter of the main earthquake of 22 May 1960, occurring at 1512 Chilean time (1112 GMT), at 38° south $73\frac{1}{2}°$ west (Ref. 5). (This would be at a point lying just off the coastline about 85 km north of Puerto Saavedra.) The following observations of macroseismic effect challenge the above epicentral location. Practically no earthquake damage occurred at 38° south; the first damage is found approximately 2° further south, in the basin of Valdivia (fig. 1 in the pocket at the back of this issue). Despite its seriousness, this damage is limited to areas within tectonically depressed basins and to areas with special subsurface geological conditions (figure 2). Continuous superficial earthquake damage begins approximately 100 kilometers south, and a definite center of intensity can be recognized near the northwest corner of Lake Llanquihue, an area whose geological setting is similar to the southern Chilean Central Valley.

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[1] In the literature, one usually finds reference to the earthquake in southern Chile. The region affected by the earthquake belongs geographically to middle Chile. The zone from Concepcion to Arauco is still in the south-central zone and the region from Valdivia to Chiloé forms the "little south" of Chile. Geographically, south Chile begins south of Chiloé (Ref. 1).

In the western districts of the city of Valdivia, almost all brick walls were knocked down, steel reinforced concrete walls were severely cracked, and most of the frame houses were broken or displaced. Takahashi (Ref. 6) estimates that the seismic acceleration for this region was about 25 to 30% of the acceleration of gravity. This indicates a Mercalli intensity of X. It should also be noted that approximately 20 kilometers east and west of Valdivia, in the towns of Heullelhue and Corral houses with rotten foundational beams survived the earthquake, which indicates that intensity VII of the above scale could not have been reached. These towns, however, are located on the crystalline schists of the coast range, whereas Valdivia is located in the middle of a tectonically depressed basin. All the habitations in the region of the crystalline coastal ranges were practically undamaged, as were the habitations near Valdivia. No damage appeared north of the town of San Jose de Mariquina (70 km northeast of Valdivia), whereas to the south, in the farm settlements, many barns and ranch houses were severely damaged. The difference in geological structure on either side of Valdivia caused exposure of upper Pleistocene gravels downvalley from San Jose de Mariquina. These gravels are found 40 meters below the level of the river in the basin of Valdivia, and are overlain by sandy and clayey alluvial sediments.

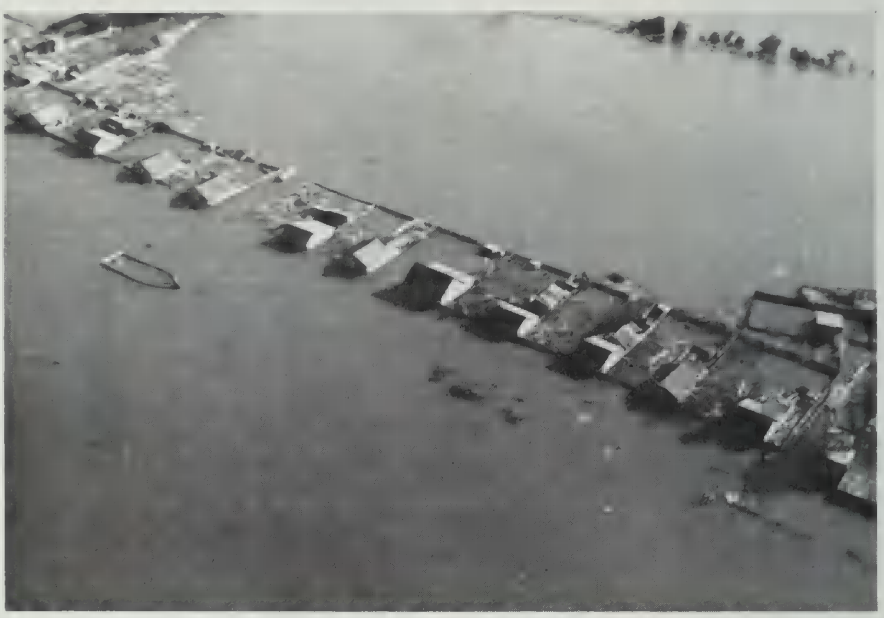

FIG. 2. This was formerly an island in the Valdivia River. Poblacion Haversbec, Valdivia Basin, after the Land Subsidence. In all, some 15,000 hectares of settled and agricultural land in the Valdivia district were submerged.

In the region of the southern Chilean Central Valley, located between the crystalline coast range and the high Cordillera, the direct results of the earthquake become more obvious as one goes south from the Province of Valdivia. The limited damage to buildings indicates an intensity of VII for the cities of La Union and Rio Bueno and their environs. In Osorno, there are few damaged houses, except for those deformed by failure of the river bank. The intensity here must be calculated as VIII, since almost all masonry walls and chimneys fell down. South of the city, damage rapidly becomes greater. In Rio Negro and environs, numerous houses collapsed,[2] and in the region between Frutillar and Octay, near the northwest corner of Lake Llanquihue, hardly a grain or hay shed was left standing or a house undamaged. North of Octay many cement walls fell down, and in doubly locked, solid, wooden houses, doors and windows were opened. In other places, 30- by 40-centimeter window panes were splintered without damage to the window frames. Between Osorno and Frutillar the railroad was disrupted at no less than 50 places, without particular subsurface phenomena being apparent at the surface. In Llanquihue, the reinforced concrete highway bridge was compressed so that water pipes along its side were bowed up. These phenomena justify the assignment of intensity X. The subsurface here is composed of exactly the same material as it is north and south of this region. Near the lakes there are, in part, well-cemented young moraines, and, farther away, gravel beds of the late Pleistocene age, situated similarly to those of the subsurface around Osorno, La Union, and Puerto Montt.

Damage south of this area becomes less severe. Excluding in this overall view the especially poor building sites in some parts of Puerto Montt (in such parts, according to Takahashi, an intensity of XI was reached), a maximum of VIII occurred in the parts of the town situated on solid ground (well-cemented moraines or gravel terraces).

The rapid decline of seismic intensity, as one goes from the central valley into the Cordillera, is interesting. Consider the following observations in a west-to-east profile just north of Lake Llanquihue: From the northwest corner of the lake where the intensity of X occurred as described above, to La Cascada on the northeast side of the lake, fallen wooden houses occurred (intensity IX). At Ensenada, at the east end of the lake, books fell out of shelves and chimneys fell from the roofs. A little farther east, on the west shore of Lake Todos los Santos, high stacks of dinner plates in the Hotel Petrohue remained standing, and at the Fundo Puntiagudo, as could be deduced from objects placed in unstable positions, the intensity could only have reached a maximum of V or VI. Here in the region of the reactivated north–south juncture of the Cordillera, the main shock was obviously restricted to a narrow zone along active faults, as will be fully discussed below.

The overall view shows an elliptical arrangement of isoseismic lines in the region of the central valley with a center near the northwest corner of Lake Llanquihue (41°S) and an isolated center in the Valdivia Basin.

Should not this state of affairs point out that the seismic determination of the epicentral location is the location of the weak beginning of the quake, which focused in a north–south trending line, and that after an initial release of energy in the northern part, the main energy was released further south?

The Epirogenetic and Tectogenetic Movements, Their Extent and Intensity

During the first hours following the earthquake of 22 May, all meadows along the lower reaches of the rivers between Rio Imperial and the south of Chiloé were flooded. In the basin of Valdivia at about 1700 hours, I observed the waters in the Calle Calle River flowing upstream with a greater velocity than I had ever seen the water flowing downstream. Days later, at the paper mill about 30 kilometers upstream from the river's mouth, marine fishes and salt water were observed. During the following month, water flooding the meadows became sweet. There occurred a loss of meadows and farmland through flooding, which amounted to 15,000 hectares in Valdivia alone.

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[2] Translator's note: See Thomas, et al, on Rio Negro.

One can ascribe this, on the one hand, to compaction of the sandy and clayey sediments, which are 40 meters thick in the Basin of Valdivia, and, on the other hand, to a definite epirogenetic-crustal movement. Because of an absence of a fixed reference for leveling, it was difficult to distinguish between the two geologic processes. The distinction was also difficult because local subsurface conditions were unknown prior to the earthquake and only the results of the earthquake could be studied. Those already familiar with the basin had no doubts from the beginning that the major process was one of crustal deformation (Ref. 3).

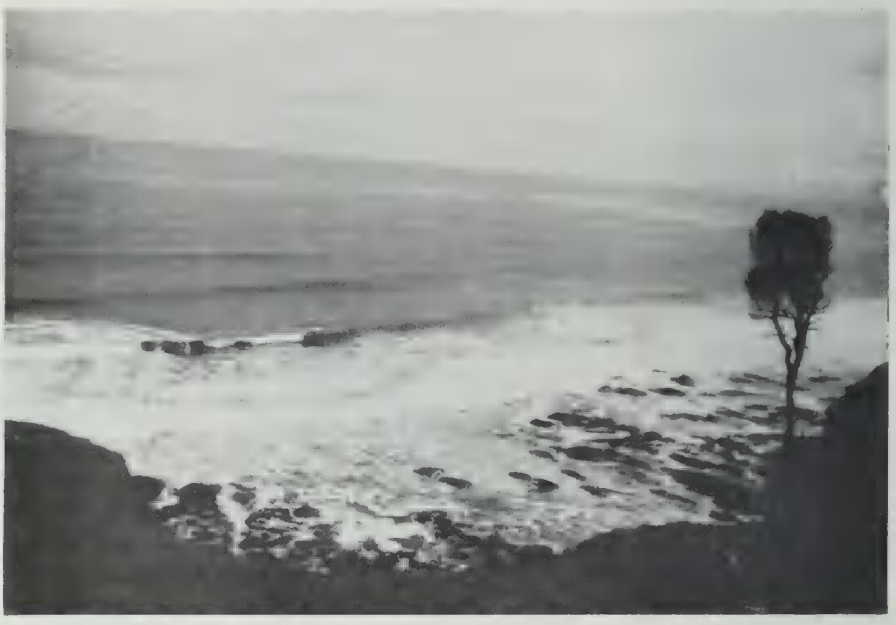

FIG. 3. Mehuin Abrasion Platform, Cut on Crystalline Schists, to the North of Playa Chica (Mehuin) Before the Epirogenetic Sinking.

Investigations already in progress showed that an epirogenetic depression of large areal proportions, associated with the earthquake, bent downward a strip of the continent about 30 kilometers wide and approximately 600 kilometers long. Along the coast, depression amounted to 1 to $1\frac{1}{2}$ meters, thereby causing the marine transgression. As evidence, the following observations from various parts of the affected continental strip can be cited:

Definite evidence of crustal deformation is seen in documented photographs from the Bay of Mehuin. The Universidad Austral established a station for marine biology there in the years prior to the earthquake. In front of the station was a fossil-abrasion platform eroded in vertical-standing phylites and crystalline schists on which zones of littoral fauna were established, as could be definitely seen in a photograph. From the photograph, it could be definitely established that water during normal tidal variations did not reach the upper levels of the platform. Today, the platform is constantly under water. An estimate of the amount of depression is possible since the high tide reaches a drainage ditch of the former station which formerly was $1\frac{1}{2}$ meters above high tide.

A comparison of figures 3 and 4 shows the sinking of the land. They show the former and present conditions near the area of the Marine Biology Station.

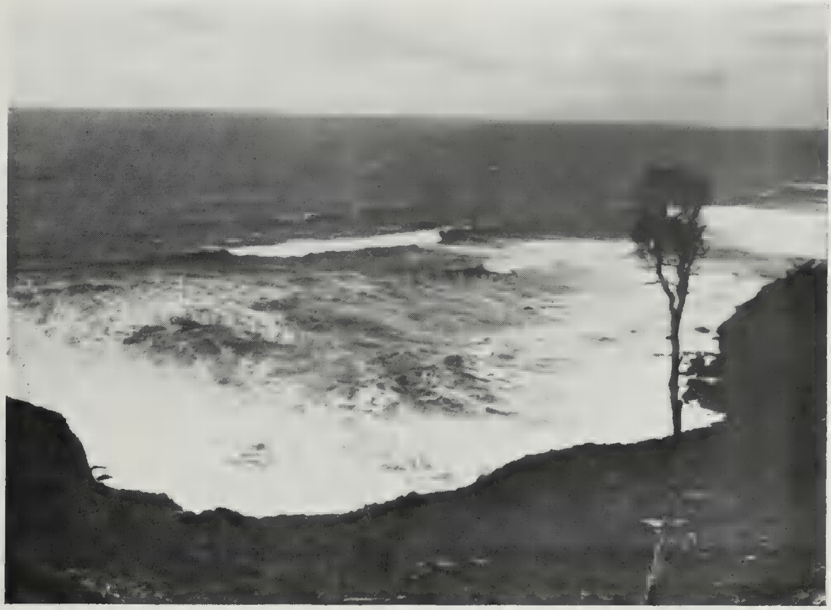

FIG. 4. The Same Abrasion Platform as in fig. 3, After the Sinking. These two pictures taken from the same point.

Further evidence for crustal movement is the fact that northwestward from the mouth of Rio Tolten, a cliff was cut into the dune sand of the almost flat coastal area. In places, the cliff cuts across a former cattle and wagon trail, as can be seen in figure 5. Geomorphic considerations show that a cliff in a flat coastal area can only be a transitional feature of short duration. In time, the equilibrium conditions of a flat coastal area will again be established.

Some fairly exact estimates of the magnitude of submergence could be made from geomorphic criteria at places along the coast. Such was the case in Puerto Saavedra, at the mouth of the Rio Imperial (fig. 6), where the difference between the new high water level in the foreground and the lowest pine-root level in the background is 1.35 meters. The true continental submergence is probably 1.5 meters, since the high water level must never have reached the lowest root level. The new high water level is at an exhumed bed of concretions.

East of Chiloé, the near shore vegetation has been dried up under the influence of salt water encroachment. At Quellon, on the east coast of Chiloé—about 70 km south of Castro, the minimum high water level is 1.30 meters above the roots of near shore bushes.

On the Rio Maullin, the depressed coastal strip extends upstream to Puerto Toledo, on the Rio Bueno almost to La Unión, on the Rio Valdivia-Calle-Calle to Huellelhue, 20 km east of Valdivia, and on the Rio Cruces to San José de la Mariquina. The harbor of Puerto Montt, which is farther from the shore, was not depressed.[3]

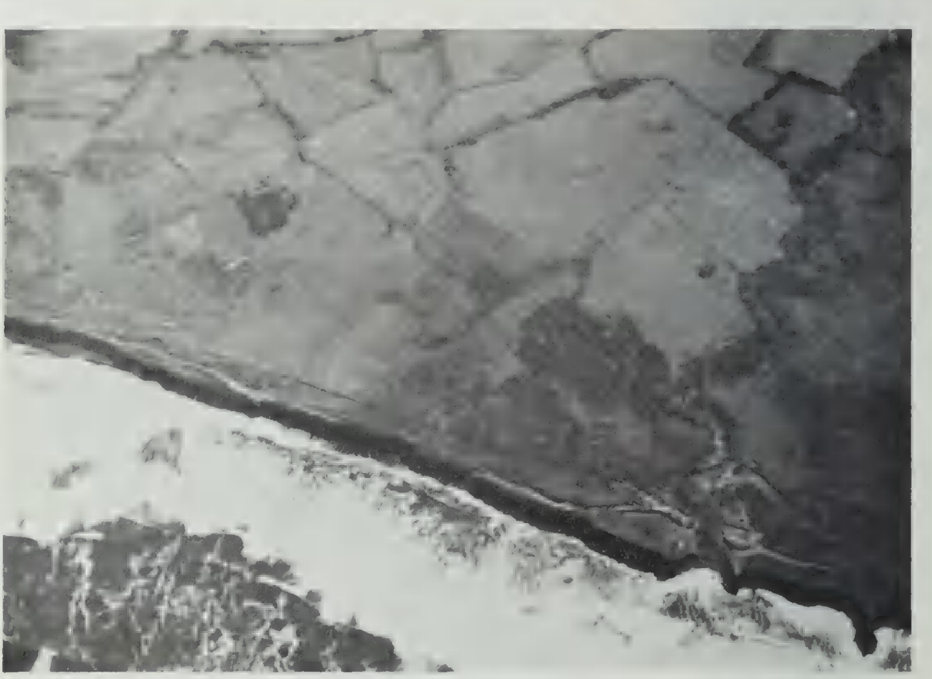

FIG. 5. View of a Fresh Cliff in Loose Sand, Northwest of Tolten. The cliff is now cut by the waves, whereas prior to 22 May 1960 there was a flat sand beach. Note the cut-off section of the wagon road. Eventually a more stable, flat beach will reform.

The northern end of epirogenetic depression must be on the southern part of the Arauco Peninsula (150 km north of Puerto Saavedra), where St. Amand (Ref. 8) and Watanabe and Karzulovic (Ref. 9) report an uplift of 1.2 meters. In the south, the Hydrographic Service of the Chilean Navy has determined a 1 to 3 meter uplift of Guafo Island (southwest of Chiloé), where two formerly separated islands are now connected by a strip of land. Therefore, the southern limit of depression could be at the road, south of Guafo toward Chiloé.

In summary, there has been a submergence of the Chilean coast from the southern Arauco Peninsula to southern Chiloé. The depressed coastal zone is about 30 kilometers wide on land, and the coast is now around 1.5 meters lower. Compaction of alluvial sediments amounted locally to a few decimeters and was governed by local conditions.

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[3] Translator's Note: See Seviers on the Tsunami (Ref. 7).

Of considerable geologic interest is the fact that, after submergence, the coast was at an older level, as shown by geomorphic features. The formerly fossil abrasion level in phylites at Mehuin has now been lowered into the region of surf action. Also mentioned was the exhumed plane of concretions at high water level near Puert Saavedra.

Figure 7, depicting an old surf-abraded cavity, shows that the new coastal level was occupied in the past. This old cavity has been covered with green algae in the months following the earthquake. Behind the isolated cliffs from which the picture was taken, there is a series of hollows excavated by the surf, which served as storage places for fuel prior to 22 May, and into which the surf has again returned at high tide.

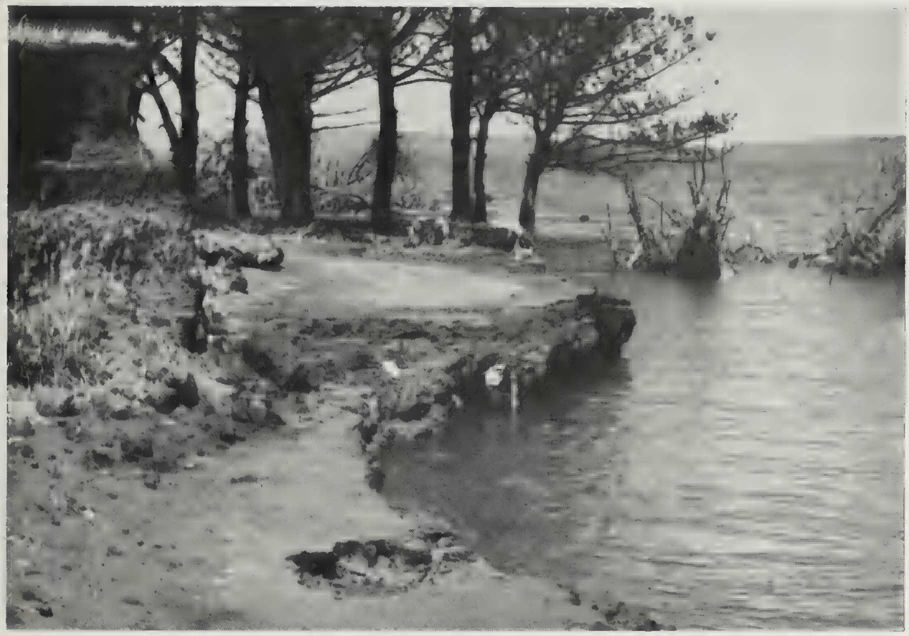

FIG. 6. View near Puerto Saavedra Showing New Abrasion Platform with an Exhumed Surface of Concretions. The root level of the pines indicates a submersion of 1.35 m.

It must be assumed that a submergence to an older level of a formerly emergent coast has occurred through crustal deformation.

THE SEISMIC SEA WAVES AND THEIR EFFECTS

Although there are no direct natural observations, one can reasonably assume that the continental shelf was included in the crustal deformation. Five seismic sea waves were recorded by the tide gages of the Chilean Navy at Valparaiso (Ref. 3). The first wave reached the coast at 1530 Chilean time, the first destructive breaker at 1620, and the last at 2130. A description of the maremoto is given in Ref. 3. Figures 8 and 9 show the lowering of the sea level in the Bay of Corral prior to the second wave, and show the wave itself, which was estimated to be about 8 meters high. The height of the waves varied with the configuration of the coast and the coastal bathymetry. An absolute height of 11½ meters was determined at the south

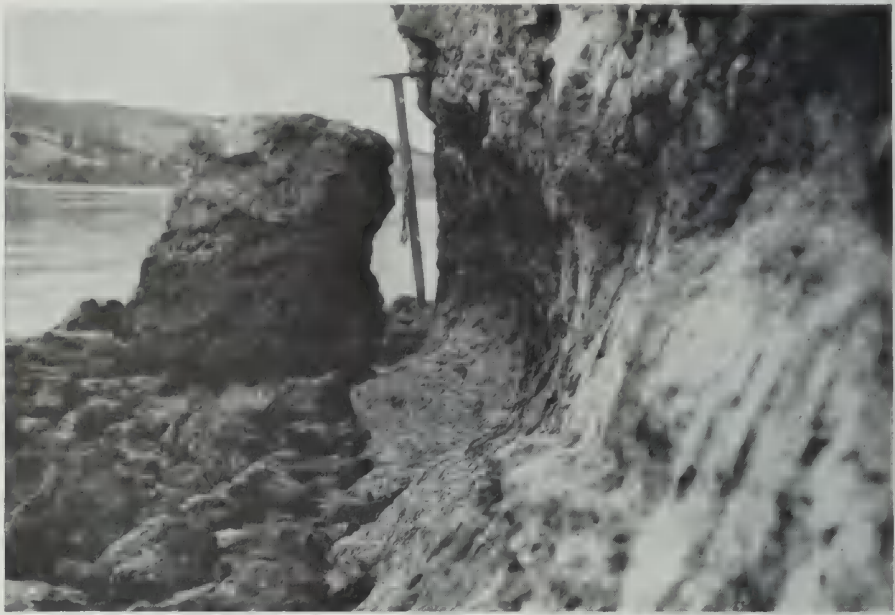

FIG. 7. Gulf of Ancud. Renewed beach erosion along a wave-cut cliff. Photo taken at low tide.

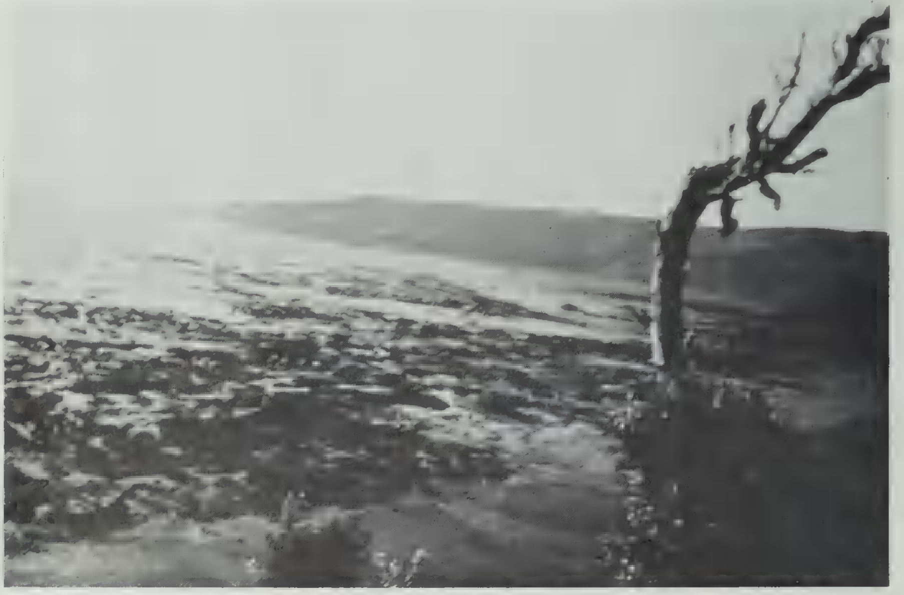

FIG. 8. Maremoto in the Gulf of Corral. Withdrawal of the sea prior to the second advance of the seismic sea wave of 22 May 1960. Taken from a cliff 30 meters high by Luis Bernucci.

corner of the Bay of Puerto Saavedra. Wave heights measured 8 meters in Mehuin, 8 meters in Corral, 7½ meters in Muiculpue, near Bahia Manza, and 5 meters in Ancud.

The radical changes which occurred in the Bay of Queule, Province of Valdivia,

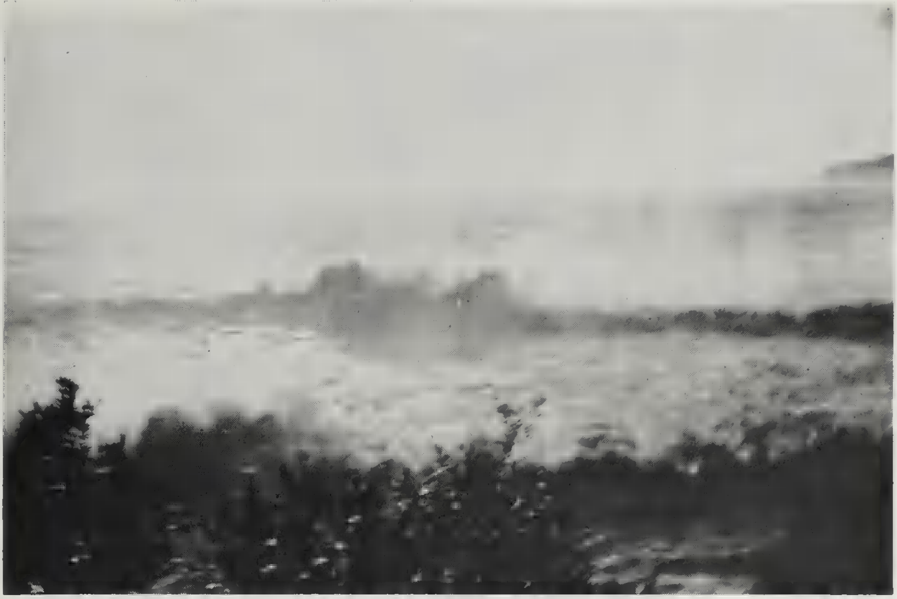

FIG. 9. Second Wave, About 8 Meters High, Breaking on Strand. Luis Bernucci photo.

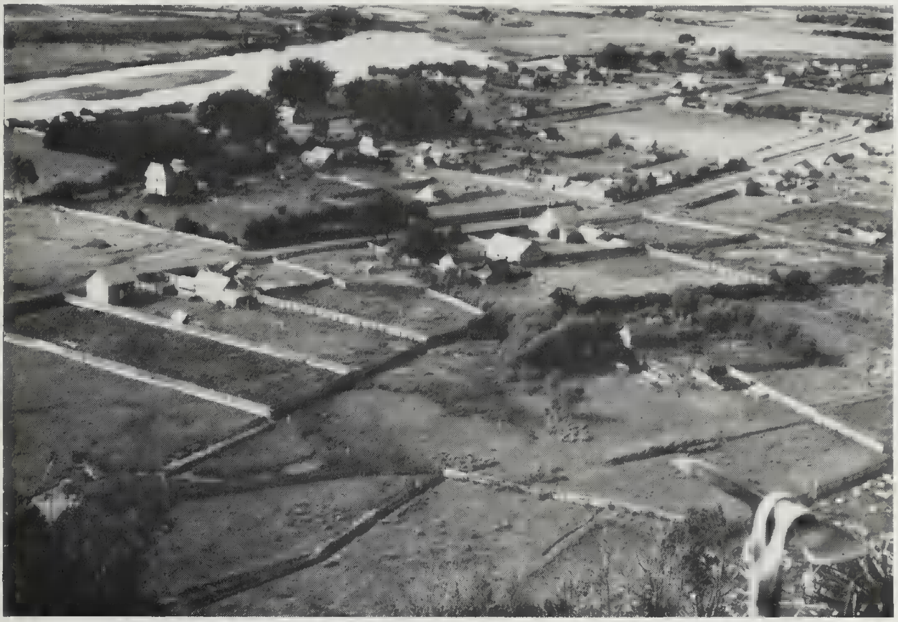

FIG. 10. Fishing Village, Queule, Valdivia Province, before the Catastrophe of May 1960.

can be seen in figs. 10 and 11, which were taken from the same place before and after the catastrophe. The breakers were still $4\frac{1}{2}$ meters high after surmounting the zone of dunes in front of the town, and the town was washed away. It is interesting to note, in the figures, the formation of an estuary from the formerly meandering creek, caused by the change in sea level.

In Puerto Saavedra, only a field of ruins remains of the former heavily populated settlement. The remains of houses are found 3 kilometers inland at the foot of the coastal hills. Houses at the shore were transported with their foundations to the highest area reached by the water, and the tides have changed the canals to 3-meter-wide rills. The whole town of Puerto Saavedra is probably a loss.

In Ancud (fig. 12), the strip of damage can be plainly seen. Here, the foundations of the fishing settlement can also be seen in the highest area reached by the water.

Aside from the destruction of coastal settlements, the submergence of the coast and the seismic sea waves have led to slower physiographic changes. The location of the mouth of Rio Imperial has been basically changed (fig. 13). After joining with the Rio Moncul, it formerly flowed 4 kilometers southward, before emptying into the sea, along a stretch where coastal sand dunes formed a relatively wide embankment. The northern crown of this dunal embankment was 30 meters high, and some remains of possible interglacial gravels and tuffs occur here. The southern area of dunal embankment was 15 to 20 meters high; the middle area was only 5 to 8 meters high and about 500 meters long. The littoral area on both sides of the embankment was bounded by a flat, sandy shore. The seismic sea waves broke over the saddle and transported some material into the adjoining marshy meadows, and formed a dam across the stream channel. This resulted in a geomorphically unstable situation. Where the river now crosses the dunal embankment, it is very shallow, and the surf breaks across it. In time, this channel will probably be closed when deposition by

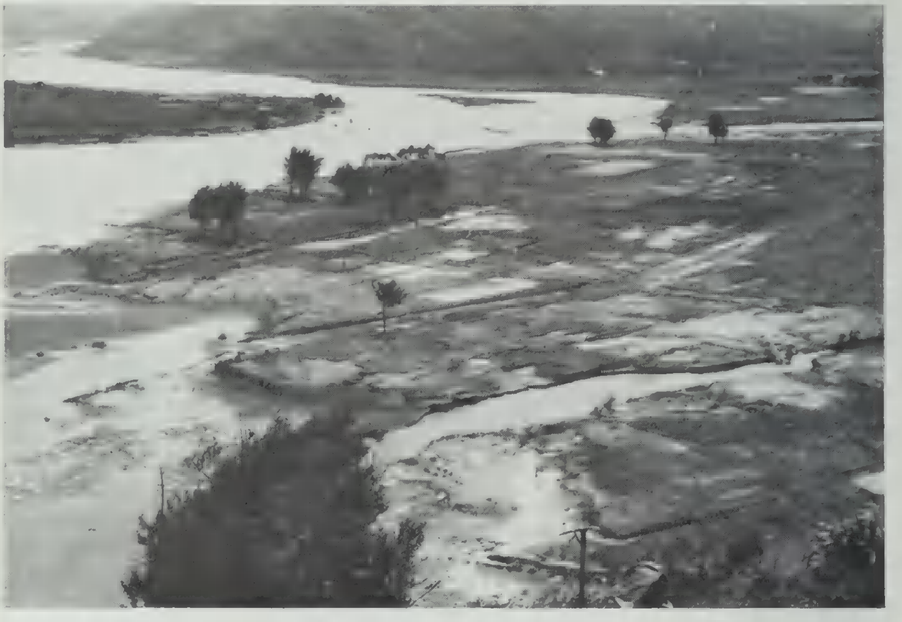

FIG. 11. The Site of Queule as Seen from the Same Point as fig. 10. The photo was taken after the land subsidence and maremoto (compare the remaining groups of trees). All houses have been washed away by the seismic waves, which were about $4\frac{1}{2}$ meters high. The sinking of the land brought about a transgression of the sea. The meandering creek bed in the foreground has been changed into an estuary.

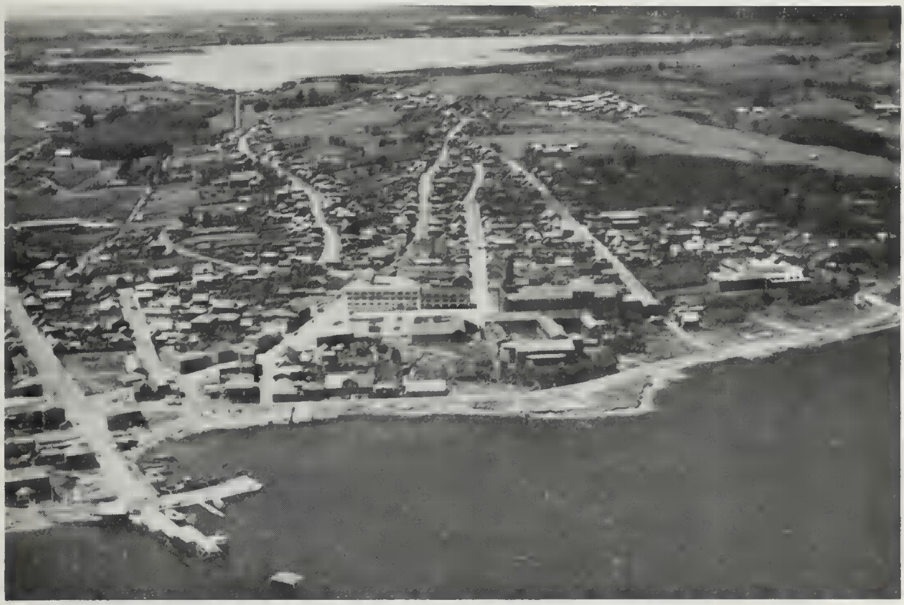

FIG. 12. Ancud, Dec. 1960. The direct earthquake damage is not evident in the picture. The seismic sea wave has washed away the structures along the shore, e.g., on both sides of the waterfront road to the right.

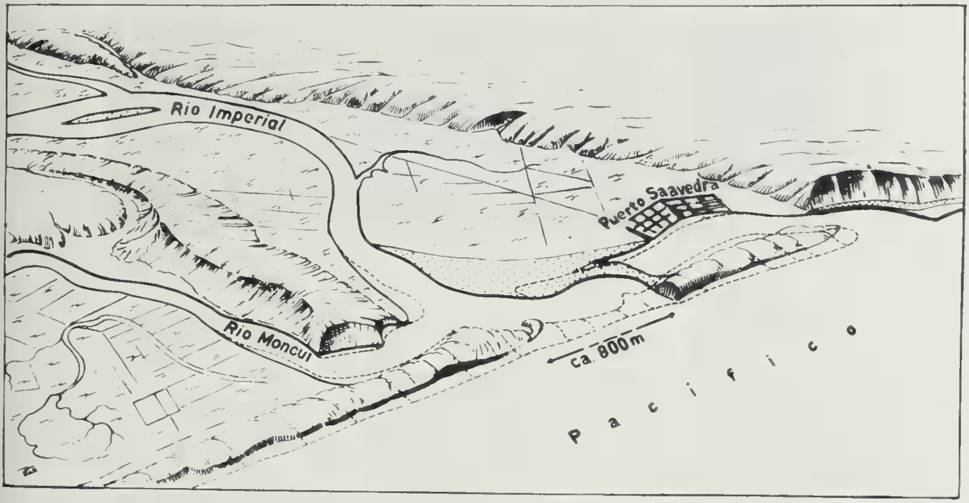

FIG. 13. Changes in the Mouth of Rio Imperial Following the Tsunami and Coastal Subsidence of 22 May 1960 (looking southeast). The former configuration is shown by the dotted lines. The sand spit has been broken by the tsunami. The river that formerly flowed to the south behind the open end of the spit now debouches directly into the sea. A sand cliff has been cut by the surf following subsidence of the region.

the surf exceeds the transporting power of the stream, such as during the time between the low summer river level and winter flood. The river will then probably return to its former deeper channel. At present only a portion of the dunal embankment is left, and it is connected to the land by a sandy embankment. The relatively higher water level has resulted in the formation of a small scarp in the sand, which at high tide is undercut by the surf, and which collapses during periods of ebb tide. In time, the shore will again become flat and the dunal embankment will remain significantly smaller than it was prior to coastal submergence.

The deepening of the Bay of Corral and the lower reaches of the Rio Valdivia is of geomorphic and commercial interest. Prior to the earthquake, the river and the bay were somewhat sanded in because of hydraulic gold mining in the middle reaches of the Rio Cruces. Ocean-going ships had difficulty going to Corral, especially at the sand bar Las Tres Hermanas, which was spreading toward the navigational channel and was at most only $1\frac{1}{2}$ to 2 meters below the water. After the earthquake, new soundings by the Hydrographic Service of the Chilean Navy showed that at the critical point of the channel, between the northern part of the sand bank and Punta Laurel, it is now 5 to 6 meters deeper, and that the bar is now $3\frac{1}{2}$ to 4 meters below the water. If coastal submergence is assumed to be about 2 meters, an erosional deepening of the channel and the water over the bank amounts to $1\frac{1}{2}$, and 2 meters, respectively. The end effect is that not only Corral but also Valdivia, 20 kilometers up-river, can be reached without difficulty by ocean-going vessels.

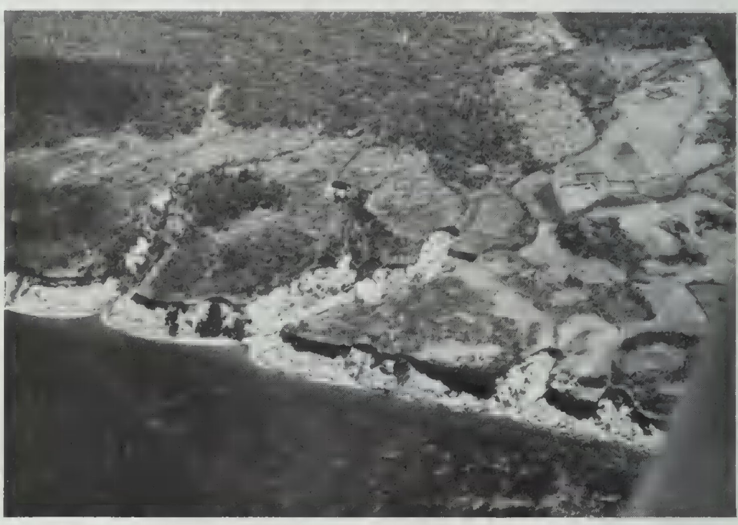

FIG. 14. Straits of Chacao Between the Mainland and Isla Chiloé. Wave-cut Cliff in Pleistocene sediments produced by the ebb and flow of the seismic sea waves.

Eroded material was not only transported seaward but also up-river, as shown by cobbles of vesicular basalt deposited in low places along the river. Because of their low specific gravity, these cobbles were transported up to Valdivia. The greatest amount of inland-transported material was not deposited along the river because it runs perpendicular to the direction from which the sea wave came; the material was deposited behind the Bay of San Juan.

In the Straits of Chacao, between the continent and Chiloe, the erosional effects of backwash, which occurred between the sea waves, is evident. The straits are bounded by sea cliffs cut into glacial and glacio-fluviatile sediments. Normally, currents in the straits are navigated with varying success by fishing ships. In many places, erosional indentations were cleaned out by tsunami waves and their strong backwash (figure 14). The material transported from the indentations is found in new bar-like deposits along flatter portions of the shore.

Where the seismic sea waves crossed the Bay of Ancud and impinged squarely against the steep coastal slopes, the cliffs retreated visibly (figure 15). In some places the surf action removed 10 meters of the Pleistocene sediments, and in others a combination of surf and slump, or caving, accounted for a removal of 40 to 50 meters.

In Golfo Ancud and Seno Reloncavi and to the east of Chiloe, no change in the configuration of the coast by erosion or surf can be seen.

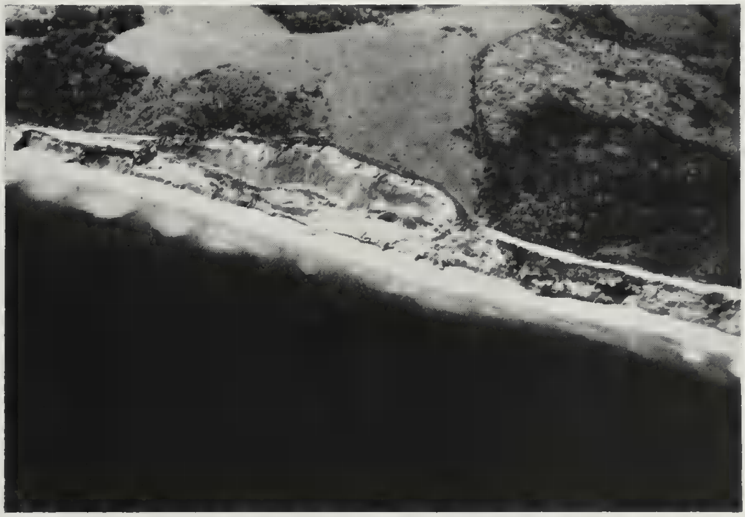

FIG. 15. Coast on West Side of Chiloé Adjacent to the Western Entrance of the Straits of Chacao. Most recent road has been destroyed by landsliding and erosion. In many places, cliffs were cut back as much as 40 meters.

LANDSLIDES, SLUMP, AND THE FORMATION OF CRACKS IN AREAS OF MAJOR REACTIVATED TECTONIC TRENDS

In discussing this complex situation it is certainly useful to clarify the state of the situation prior to the event. In the area of interest, there are no geologic maps with a scale greater than 1:500,000. The most recent general geologic map of Chile (Ref. 10), at a scale of 1:1,000,000, shows no structural elements and only the most general geologic units. This situation probably exists because the whole Cordillera in the "little south" has a thick forest growing on a varying thickness of recent tuff. Therefore, mass transport created many new outcrops.

Most landslides and slumps are concentrated in a relatively narrow strip which, surprisingly enough, is not at the foot of, but within, the high Cordillera. When one flies over the glacial furrow occupied by the southern Chilean lakes, into the Cordillera, the first sparse, local landslides appear 20 to 25 kilometers from the mountain range's topographic boundary. At a distance of 25–30 kilometers from this boundary, a definite zone appears in which the slides are close together and mountain flanks are bare for many square kilometers because of a slumping of the tuff layer or landsliding of weathered rock. In many parts of this zone only $\frac{1}{4}$ of the forest remains. The zone ends 8 to 10 kilometers to the east as definitely as it begins. This zone is about 10 kilometers wide in the south at Lake Todos los Santos, 8 kilometers wide at Lake Rupanco, and 10 kilometers wide at Lakes Ranco and Panguipulli. From the east end of Lake Calafquen, to the Pellaifa, hinterland, the zone broadens to almost 20 kilometers, and shrinks to 8 kilometers again at Volcan Villarica. Further north, no important landslides were encountered. In the zone, not only have sections of the tuffaceous cover slid over the underlying rocks, but landslides in volcanic and plutonic rocks have also occurred. The former occur in the Sierra, Santa Domingo, and Cerro La Picada on both sides of Lake Todos los Santos, and the latter are especially well seen on both sides of the eastern end of Lake Rupanco at Puntiagudo.

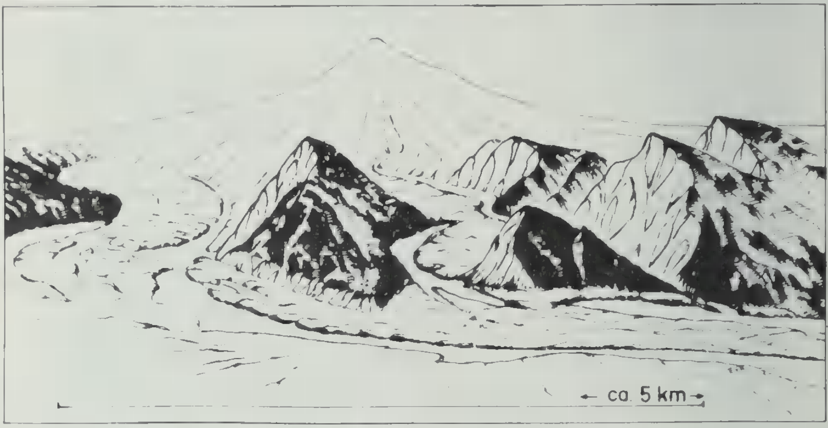

FIG. 16. Northern Side of Volcan Villarica (looking south).

Once the topographic conditions for some of the slides were recognized, a likely zone for the localization of the slides was suspected from the topography. The suspected zone trends N13°E in a line beginning at the north end of the Estero Reloncavi, extending across Ensenada Cahutue, over the volcanics of Puntiagudo, along the eastward extension of Lake Rupanco, and from the group of volcanos around Casablanca to those around Puyehue where the eruption on the day following the earthquake occurred. Further to the north, the line extends just east of Lake Ranco, across the furrow of Lake Neltulme (east of Lake Panguipulli), over the divide between Lakes Calafquen and Pellaifa to the volcano Villarica. The suspected line was confirmed by field observations. The zone of landslides points out a zone of depression within the Cordillera, which is broken by younger volcanoes, as can be plainly seen from the air. For instance, in the valley north of the volcano Villarica (figure 16), the westerly wall is gentle and the easterly wall is cliff-like. This asymmetry is marked by the fresh landslips, which have removed much of the vegetation and weathered cover on steeper slopes, exposing light-colored silicic plutonic rocks, granite or granodiorite. The rocks themselves tell us little about the structure, but the land form is one of tilted blocks that have been uplifted and faulted more on the east than on the west. The areas between these tilted (uplifted) blocks are not the types of valleys seen elsewhere in the Cordillera. They are probably not erosional valleys formed by ice, since there is not sufficient area for ice accumulation, and there are no traces of glacial abrasion on the valley walls. Instead, there occur outcrops of landslip debris up to 50 meters above the stream in contact with volcanic ash upstream. These deposits form terraces in the outer reaches of the valley. From these observations, it can be concluded that the areas between the tilted blocks were filled with pyroclastic sediments.

Similar conditions occur on the north side of Volcan Puyehue. Figure 17 is a view south toward the volcano, showing the elongate trough. In the foreground, along the tectonic trend, is the Maar de Caran and the crater of Rininahue. Both have been formed in recent decades. In the southward extension of the valley are found the lava flows extruded from the seven vents active after the earthquake.

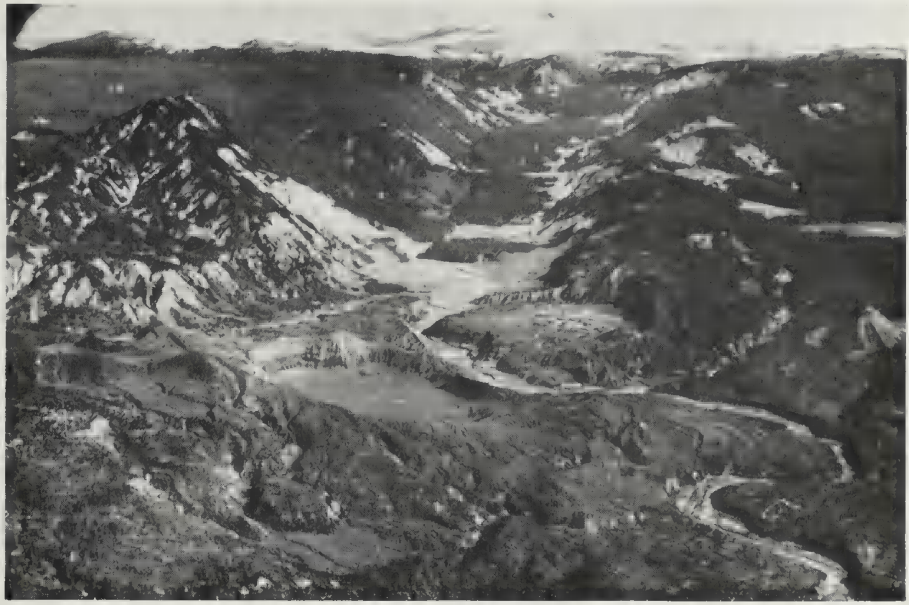

Fig. 17. View South Toward Volcan Puheyue. The photo, taken over the "Graben", shows the Maar de Caran, crater of Riñinahue and numerous recent landslides.

The eastern boundary of the fault zone is again in plutonic rocks, which, because of their scaly structure, promote the formation of steep mountains. In these plutonics the zone of landslip ends as suddenly as it begins. Farther south, in the area east of Lake Rupanco, similar conditions occur.

From the above observations it can be concluded that the zone of landslip marks a graben-like structural zone with tilted blocks located within the Cordillera. This fault zone was shaken by the earthquake, but no slip along the fault during the quake could be shown.[4]

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[4] Translator's note: This zone is the trough of the Reloncavi fault zone.

A question still remaining concerns the cause of the landslip zones in the area east of Lakes Rinihue, Panguipulli, and Calafquen, which are sometimes twice as wide as those further south. In the cross valleys of Lakes Calafquen and Pellaifa, there occur deposits of landslip debris in a 22-kilometer-long, east- and west-trending body. This does not include a second 1-to-2-kilometer-wide zone of landslip just west of the above-mentioned lakes.

The following observations were made around Lakes Calafquen and Pellaifa (Figure 18). On the south side of Lake Calafquen, the unrilled, little-eroded wall is covered with landslide scars. These scars expose outcrops of gently westward-dipping volcanics. A large rockflow of landslide debris has come from the first cross valley, that of Estero Lingoico, and it has entered the western part of Lake Pellaifa, damming it so that the water became about 8 meters deeper. The Lingoico cross valley marks the contact between volcanics on the west and granodiorite on the east. The contact can be followed along a N13°E strike to the south side of Lake Villarica and from there to a similar small graben. It is therefore an extension of the aforementioned fault zone.

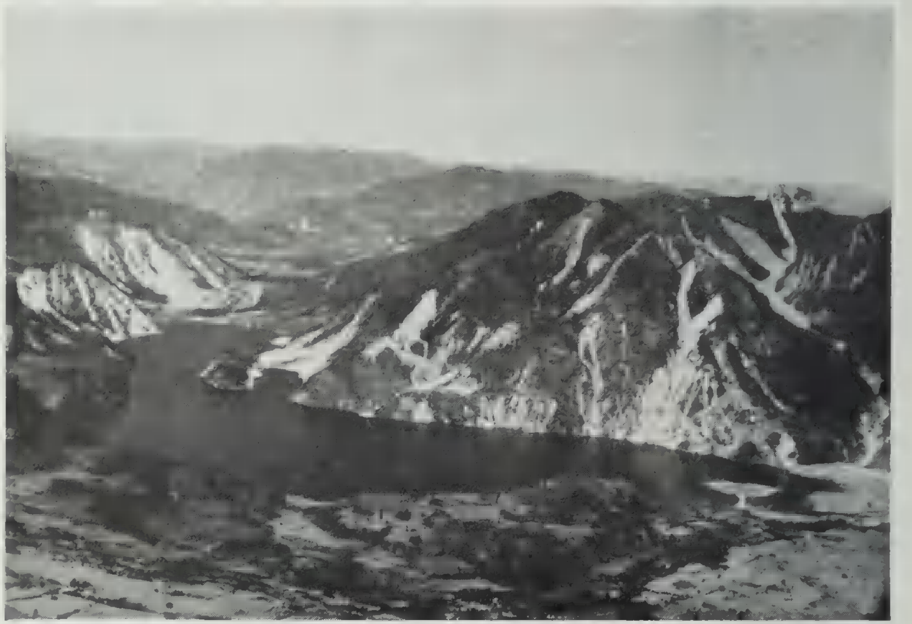

FIG. 18. Landslide Zone in the Region of the Transverse Groove of Lago Pellaifa. The view was taken toward the southeast. The avalanche to the right has closed the outlet of the lake and raised its level 8 meters. The nearest portion of the lake and foreground lie in the Reloncavi fault or "Graven zone".

The landslips are not confined to the aforementioned places. Eleven kilometers eastward, in the granodiorite, slips occur in greater profusion.

One of the largest landslides occurs on the south side of Cerro Aniques, west of Lake Calafquén, and its deposits obscured the Hot Springs of Malihue, including inhabitants and cattle. On the flank of Aniques, a series of gray lamprophyre dikes striking SSW-ENE occur, which are morphologically expressed as slots. They belong to the tectonic feature shown in figure 1, the line lying west of Lakes Riñihue, Panquipulli, and Calafquén. This tectonic feature is a graben. During the earthquake the walls of this graben were severely shaken, and on the west side of Lake Riñihue this led to the greatest deposition of rock debris (Ref. 4). In the steep-sided canyon of the Rio San Pedro, which is 80 meters deep and has a maximum width of 500 meters, 4 landslip dams occurred. The total closure of these 4 dams is estimated to have been about 5 million cubic meters. The largest of these (figure 19), which originated from the river bank, was more than 1,100 meters wide, and the lowest part of the crown was 40 meters high, i.e. 26 meters above the level of Lake Rinihue.

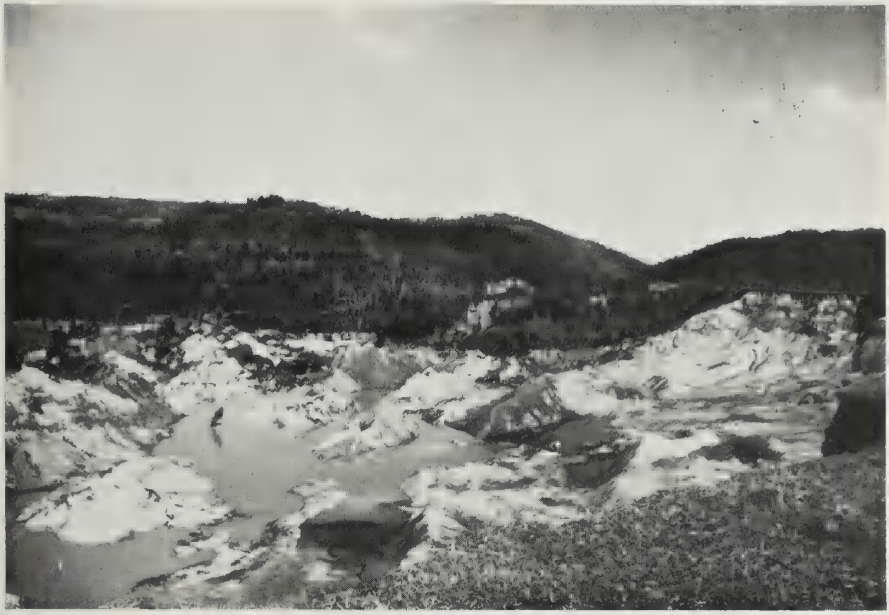

FIG. 19. Obstruction of the San Pedro Valley. This was a result of sliding of varved clays and hanging Pleistocene gravel banks and moraines. About 4,700 square kilometers of drainage was cut off for 2 months, and Lago Riñihue rose 26 meters. When the lake overflowed, 3×10^9 cubic meters of water escaped.

This large landslip deposit traveled 500 meters horizontally with a vertical drop of only 50 meters. This was possible because of special petrographic and stratigraphic conditions. The Rio San Pedro was first cut into 80 meters of Pleistocene sediments, of which the lower 40 meters are finegrained, thixotropic, varved lake sediments. Upon being vibrated, these sediments practically liquefy, becoming a porridge-like flowing mass. This occurred during the earthquake, and the upper 40 meters of conglomerate, sand, and morainal material slid across the canyon over the finer, liquefied sediments. All available methods of lowering the dam were tried, but in the two months of attempts to lower the spillway, the weather succeeded in filling the lake 26 meters above its former level, and about 3 million cubic meters of water stood ready to break through the dam on 24 July when overflowing began. In 30 hours, the largest dam was completely cut through. Fortunately, the river entered a 50-meter-wide winding canyon just a few hundred meters downstream from the dam. In spite of this canyon, the 1-kilometer wide floor of the valley on either side of Rio Calle Calle was flooded 5 and 6 meters deep just east of Valdivia, between Los Lagos and Cuesta (figure 20). As a result of this flood, many buildings were carried away, areas in the valley were covered with gravel and sand, hundreds of thousands of cubic meters of wood were carried into the sea, and the railroad grades and roads were washed away. Because of adequate warning, no people were injured.

West of the intramontaine graben and the Lakes Rinihue, Panguipulli, and Calafquen, the SSW ENE trend is conformable with the Andean foreland. The interruption of the central Chilean valley by the coastal Cordillera occurs along this trend, as do longer stretches of the coast north of Valdivia.

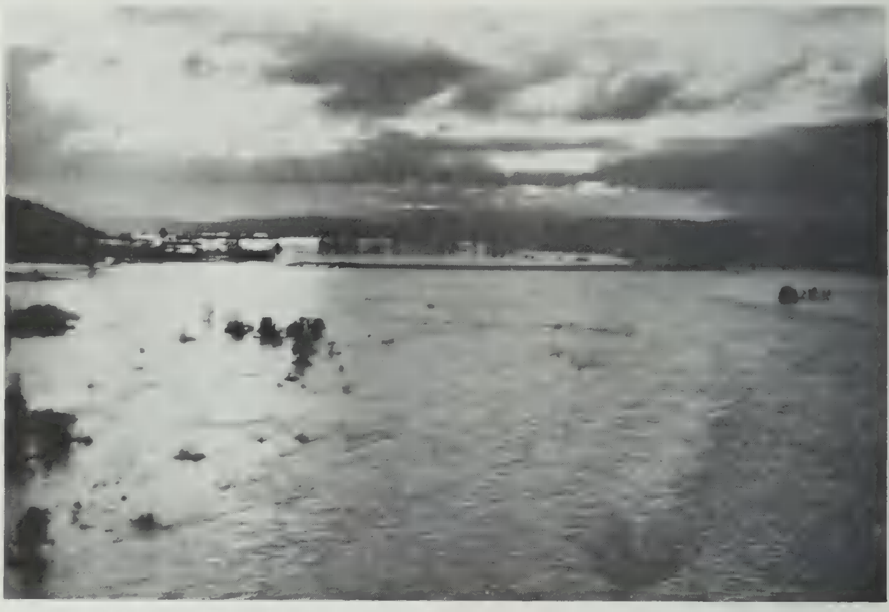

FIG. 20. The 1-Kilometer-Wide Valley of the Calle-Calle River. View of the railroad bridge of Antilhue during the outflow of the water from Lago Riñihue. The peak of the flood has already passed.

At the northern end of the SSW-ENE-trending coastline between Corral and Mehuin, where it turns northward, there occurs a crack formed during the earthquake (figure 21). This crack cuts the E-W-striking structure of the crystalline schist in a SSW-ENE direction and can be followed hundreds of meters up the coastal embankment until it disappears under soil and forest. In solid cliffs, the crack varies in width from 1 to 2 centimeters, and it shows no differential movement.

With moderate caution, let us consider observations of landslip in the flatland west of Lake Llanquihue. Noteworthy are the numerous landslides at isolated places on the steep banks of the Maullin River by Puerto Toledo, even though no special conditions of the bank or its material at these places exist. Possibly these are the slides which Tazieff called attention to (Ref. 11), and which Lomnitz also observed. It is worthy of note that these slides are located on the projection of a lineament marked by geologic and geomorphic features. The lineament begins at the volcanics of Puntiagudo, extends over a ridge to the volcano of Osorno and its row of fresh parasitic cones accompanied on both sides of the Cordillera La Picada by many landslides. The lineament crosses the volcano Osorno, on whose northern side slides in volcanic ashes occurred during the earthquake, destroying a ski hut. Along the lineament's extension on the southwest side of the volcano occur the youngest parasitic cones, and eastward from the foot of the Bahia del Volcan landslides in basalt occur in a confined zone. The lineament extends further along the peculiarly straight SE shore of Lake Llanquihue, and from there out into the flatland to the banks of the Maullin River where the above-mentioned slides occurred. The river bed itself is peculiar at this place in terms of its hydrology and geomorphology. Along certain stretches, the river is hidden from the aerial observer by a dense heath, and the water emerges from the heath in two relatively low waterfalls. Time did not allow a more thorough investigation of details. However, all my observations from Puntiagudo to the above-mentioned waterfalls support the idea that this lineament may have been formed as a manifestation of movement in the Andes similar to that studied in the Mexican Cordillera.

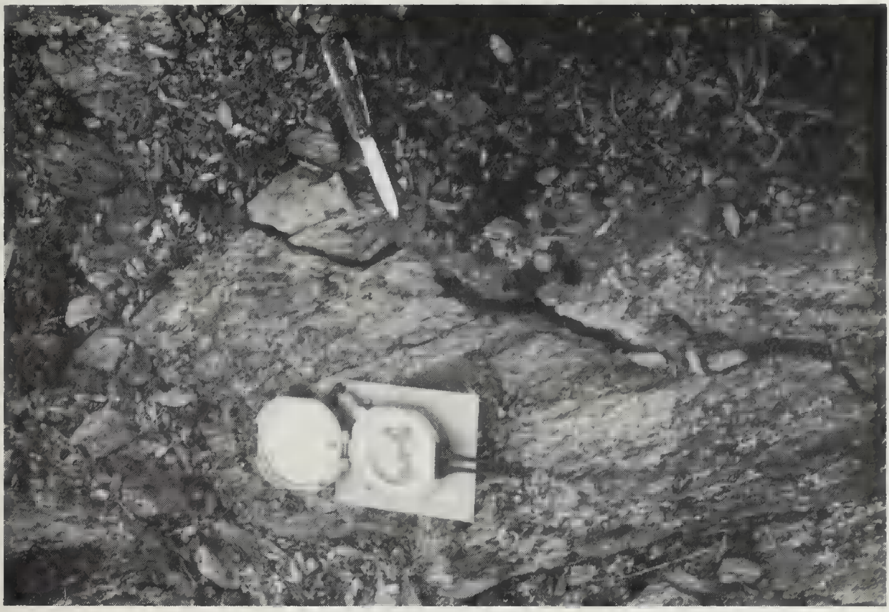

FIG. 21. SSW-ENE Fracture in Crystalline Schists on the Coast North of Mehuin.

In conclusion, consider some observations on the number of earthquakes similar to those of 22 May 1960. In front of the unstable upper cliff of Cerro Aniques, west of Lake Calafquen, about 150 meters above the valley floor, there begins a heap of landslide debris. The center of this heap has been cut to its bottom by a creek. Exposed in the creek walls, the granodiorite basement is first covered by 2 meters of gravel mixed with lapilli ash. Then follows a light colored lapilli tuff. Above this, there occurs only landslide debris cut at four horizons by humus (soil).

In the whole Cordillera of Southern Chile one can observe that the fresh, icepolished basement is covered by a tuff without the development of a weathered zone. One knows from the sequence of tuffs overlying the moraines of the Andean foreland that the tuff was deposited immediately after the deglaciation (Ref. 12).

Therefore, if four landslides occur over the tuff at the foot of Cerro Aniques, one can assume with certainty that, since the last glaciation, or in the last 6,000–8,000 years, this tectonic lineament has experienced four earthquakes of a magnitude and with extraordinary results like that of 22 May 1960.

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THE DISTRIBUTION OF THE DAMAGE CAUSED BY THE EARTHQUAKE IN VALDIVIA IN RELATION TO THE FORM OF THE TERRANE

By Wolfgang Weischet

(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

The western part of the city of Valdivia is more severely damaged than the eastern part. This is because the eastern part is underlain by a firm continuous bed, actually a terrace, of *cancagua*, a fine-grained soil composed of volcanic ash. The western part consists of a discontinuous surface marked by isolated mesa-like remnants of this terrace, surrounded by soft, incompetent fill. Vibration of the mesa-like columns was severe because of the lack of contiguous support at the contact with the incompetent fill material. Construction on artificial fill was very seriously damaged.

Structural and Environmental Damage

Figure 1 (in pocket at rear) shows the damage that resulted from the earthquake of 22 May 1960 within the urban limits of the city of Valdivia. The damage to habitations, factories, and other buildings; the destroyed portions of bridges and streets; that part of the city that remains below water as a consequence of the settling of the lands, have all been delineated.

The damage was noted object by object, on a map of the city (scale of 1 to 5,000), by personnel of the Instituto de Geografia of the Universidad Austral de Chile. Notes were made as to the material of a building, the number of floors, and the seriousness of the damage. It was also noted if a building was only thrown a little out of plumb, as in the case of houses of wood; if all the walls were cracked in houses of other material; or if a house had fallen down or had slid as a unit over the fill upon which it was placed.

Cracks in the streets, their extension and direction, and the direction of the displacement of the material at the side of the cracks have all been indicated. The damaged parts of bridges have been indicated. All indications of damage are correlated with visible evidence. Particularity of construction, such as the architectural details, remains outside the interest of this inquiry, for we sought only to relate the distribution of the damage to the surroundings as a basis for interpretation of the origin of the damage.

In the environmental distribution of the damage, a distinct division of the city into a (strongly destroyed) western part and a (scarcely damaged) eastern part is observed. The line of demarcation runs approximately from the bridge Las Animas through Calles Pedro Montt, Baquedano, Clemente Escobar, and Bueras to the northern point of the island.

The eastern districts of the city are newer and, in part, better constructed, but a number of constructions that were weaker than some in the western district did not fall down. By many examples, it may be shown that the destructive forces were less in the eastern part of the city than in the western part, with the exception of the streets near the railway station. Those parts were excluded where the Recent fill serves as the base for bad foundations. The comparison, over similar conditions of subsoil, of the damage near the plaza or in the Calle de Peninsula with the damage in the Calle Errazuriz or in the vicinity of the old water tank between Picarte and Errazuriz leaves no doubt that the accelerations during the earthquake were greater in the west than in the east of Valdivia.

Physical Characteristics

An intimate relation is shown between the distribution of earthquake damage, the topography, and the geomorphologic structure of the subsoil.

A topographic profile of Valdivia, from the new construction of the Colegio Aleman on the Isla Teja, through the Plaza at the intersection of Calle Beaucheff with Pedro de Valdivia, and through the municipal park, Calle Errazuriz, is presented slightly schematized in figure 2.

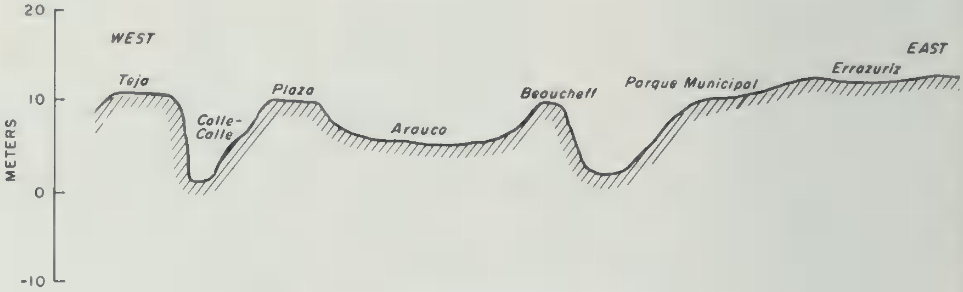

Fig. 2. Topographic Profile of Valdivia.

In the west, some superficial remains of horizontal surfaces in the form of elevated islands stand about 9 meters above the level of the river and are surrounded by the so-called "bajos," relatively flat depressions of the land, which were filled and artificially leveled with debris. In the east, a high and continuous terrane reaches widely to a level of 9 to 12 meters and is subdivided only superficially by little basins.

The limit between the two different geomorphologic formations coincides exactly with the line mentioned above that separates the two sectors of the city that have been devastated, one more strongly than the other.

It may be shown that in the part where the higher terrane has remained united, compact, and not divided, the destructive forces were less than in the part where remains of high terranes are surrounded by low areas. This is not a consequence of the location of the high spot, as can be demonstrated once again in the comparison of the Calle Independencia and the vicinity of Errazuriz, but depends on the composition of the remains of the terrace, with the low spots that surround it on one side and the plane of the continuous terrace on the other.

This seems comprehensible if one unites the results of study of the few wells within the city limits with the history of the geomorphologic formation of the basin of Valdivia and a concept of the composition of the subsoil.

On the banks of the river that surrounds the plains of the eastern terrace is encountered a cemented, coffee-colored sediment, composed of sandy or clayey material called *cancagua.* It was derived from volcanic ash and deposited under muddy conditions in bays of the sea. Gravel is not encountered in this material.

The age of this sedimentation has been interpreted differently by different colleagues. It is certain that it dates from the Glacial Epoch. While H. Illies places the sedimentation at the close of the Glacial Epoch and W. Wetsel considers it as the sediment of the last or next-to-last glaciation, the writer considers it more probable that it comes from the last interglacial period, for the following reasons: In the first place, its location corresponds in altitude to the level of the sea at that time. It possesses a thick soil profile, too well developed to be only of postglacial origin. The thickness of the *cancagua* diminishes above the river as one goes upstream and disappears where the level of the river reaches an altitude of 10 meters above the level of the sea, a little upstream of Huellelhue, where the fluvial sediments of the last glaciation are in the form of fresh gravel occupying all the bottom of the valley.

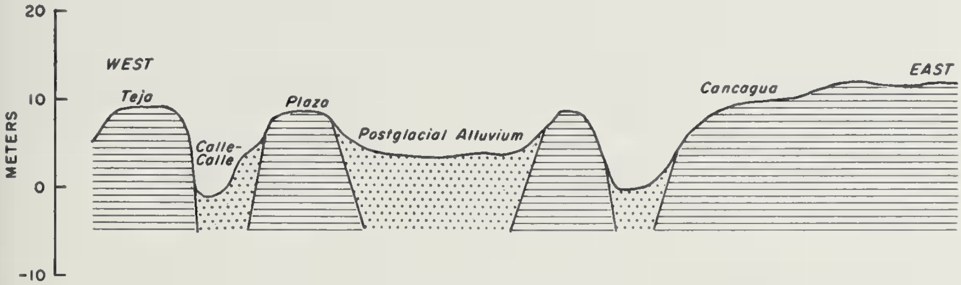

FIG. 3. Comparison of Soil Formation in East and West Sections of Valdivia.

It is therefore probable that the *cancagua* and its terraces were deposited before the last glaciation. Therefore it must be considered that the remains of the terraces between the low spots in the western part of the city form only the tops of well-pronounced little hills, which extend a certain distance as isolated ridges, without firm connections between them, only communicating with more Recent fill.

During the last glacial epoch the level of the sea lowered all over the world a total of several decameters. All of the rivers, including the Valdivia, had to carve their way into the terrane near their mouths. In one well in Calle Bueras, boulders, which are commonly considered as corresponding to those of a glacial epoch, appear at a depth of only 42 meters (1 to 2 meters, more or less, above the river or sea level). Small side valleys of the Valdivia River have been intercut in the edge of the sedimentation of the *cancagua* in such a manner that at the foot of the united platform on the east, undulating, deeply incised remnants of the terrace stood within what is now the western part of the city. When the level of the sea came up again at the end of the glacial epoch, the slow refilling of the concave parts between the ridges took place with new and soft sediments (figure 3). These are, once again, *cancagua* followed by clay, mud, sands, and sediments of putrid muck, such as appear in the upper 17 meters of the wells in Calle Bueras. Thus, there would appear to exist in the western part of the city, as much as 20 meters below the level of the river, a relief that consists of the remnants of terraces, and semiconsolidated masses of *cancagua* that were widely separated as if they were solitary castles surrounded by masses of soft and recently sedimented fill (natural fill in the low parts).

During the vibration of an earthquake, these castles lack coherence; they bob around much like the pillars of a bridge that rests on the sandy subsoil of a river. On the other hand, the united platform on the eastern part of the city does not oscillate as strongly. The consequence of all this is that the damage shows wide differences in severity in different parts of the Valdivia. Similar differences are observed by every person who travels to the Cuesta de Soto and to the villages upstream or toward Corral. These populations, situated over a solid base on the slopes of the crystalline states, have suffered practically no direct damage from the effects of the earthquake.

It should also be pointed out that the second distribution of damage is less dependent on the position of the city. Grave damage is always encountered near the edge of the remains of terraces, in spite of the fact that the subsoil for the construction may be quite firm and solid. A third, but well known, widely discussed, and complicated source of damage is the artificial fills of the earth, over which houses were not destroyed by direct effects of acceleration during the earthquakes but by the fracturing or breaking of the foundation.

Because of these observations, the writer considers the danger of damage by earthquakes to be greater in the western part of Valdivia than in the eastern, even when the subsoil for construction located beneath the area is acceptable in itself.

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RELATION BETWEEN GEOLOGY AND THE EFFECTS OF THE EARTHQUAKES OF MAY 1960 IN THE CITY OF CASTRO AND VICINITY, CHILOÉ

By Carlos Galli O. and Joaquin Sanchez R.

(Translation by Pierre Saint-Amand)

ABSTRACT

The rocks and sediments of the region have been divided into eight units: metamorphic rocks of pre-Mesozoic age, composed of mica schists; volcanic rocks, columnar andesites, tentatively assigned to the Tertiary, that outcrop in a small area to the west of Castro; fluvioglacial deposits, uncemented sands and gravels that in almost all cases overlie three terraces of Pleistocene age that are indicated on the map as morphologic units; slope deposits, friable hybrid material neither classified nor consolidated, that cover one of the most dangerous areas in which to construct; beach deposits—unconsolidated coastal sediments; unconsolidated alluvial sediments distributed in the beds of rivers and in the river deltas presently in formation; and deposits of artificial fill, gravels, sands, bricks, trash, etc.

Damage to structures is clearly related to the geology. In areas of artificial fill and of slope deposits, catastrophic destruction was caused almost exclusively by geologic and morphologic factors. Some areas with a favorable morphology, such as the intermediate and high terraces, are formed of sound material, such as metamorphic rocks, and had little or no damage.

Introduction

The city of Castro, capital of the department of the same name, is located on Isla Grande de Chiloé, along the western edge of Castro Fiord at the mouth of Rio Gamboa, (figure 1). Castro has a population of about 8,500 and a surface area of 1.5 sq km. The principal industries are agriculture, livestock, fishing, and wood. Second-class roads lead to the neighboring villages of Chonchi, Ralcahue, and Kuemchi. A gravel road and a narrow-gage railway unite Castro with Ancud, the capital of the province. The railway was paralyzed from damage caused by the earthquake.

The object of this study was to collect geologic information about Castro and environs, in order to establish relations between the characteristics of the ground that underlies the city and the effects of the earthquake of May 1960 upon the works of man.

The work consisted of a preliminary geologic mapping of the urban areas and of the areas of possible extension of the town (figure 2 in the pocket at the back). The work was done between the 23rd and 31st of August, 1960. The topographic base used was the Plan Regulador de Castro (scale 1:2,000) of the Institute of Housing, Urbanism, and Planning of the University of Chile. For detailed geologic work the map is deficient. In the plan are indicated lithologic units, morphologic units recognized in the terrane, contacts, structural basins, areas of slide material, terraces, etc.

Vertical aerial photographs of the zone, taken after the earthquake by the Chilean Air Force (FACH), were used to good advantage. A census of the damage, made by the Institute of Urbanism and Planning of the University of Chile, was used to make the table of damage with respect to geology.

Relief and Drainage: Castro is situated on a terrace between 35 and 50 meters above sea level. Other terraces of different altitudes exist in the neighborhood of the city. Rio Gamboa drains an area immediately to the west of Castro, and a small creek drains the north side of the city. Rio Gamboa rises in Cordillera de Piuchue, a northerly trending mountain chain some 10 km to the west of Castro, and debouches into Castro Fiord. The stream to the north of Castro arises in the mesas to the northwest only 5 km from its mouth in Castro Fiord.

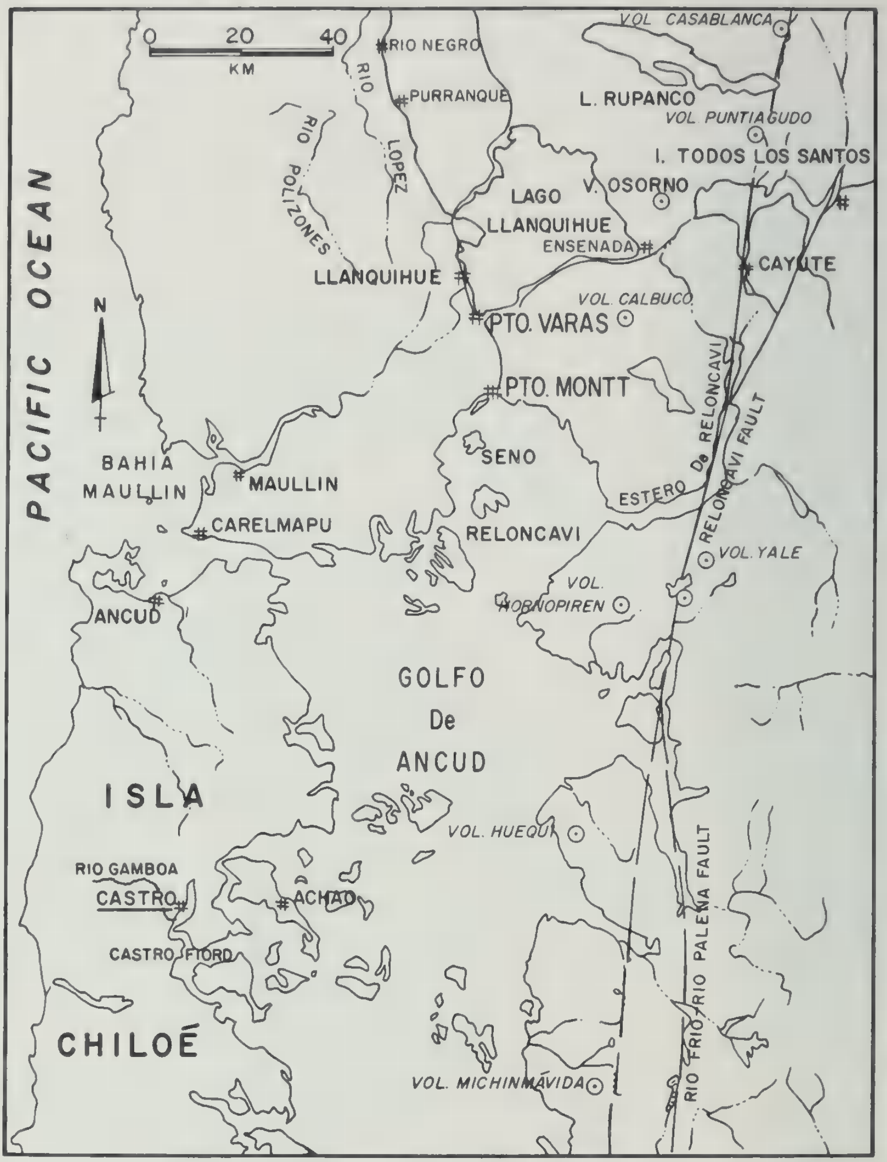

Fig. 1. Map of Earthquake Region.

GEOLOGY

Metamorphic Rocks: Metamorphic rocks of unknown, but probably pre-Mesozoic age, are exposed along the banks of Rio Gamboa, especially in a deep canyon near the hydroelectric center.

The metamorphic rocks are mainly mica schists contorted by microfolds and containing nodular injections of quartz.

The contact between the metamorphic rocks and the younger rocks is covered in almost all parts; but they are probably in angular discordance with the overlying formations. The metamorphic rocks are relatively fresh and hard and are the best foundational material in the vicinity.

Volcanic Rocks: The volcanic rocks crop out in the vicinity of the hydroelectric plant in a very small area partly covered by talus and vegetation.

The age is unknown, but the aspect of these rocks is reminiscent of the andesites of the lower-Tertiary and middle-Tertiary Argentine mountains and is the only support the authors have for including them tentatively in the Tertiary. The volcanic rocks are gray hornblende andesites with phenocrysts about 5 mm in diameter. The rocks have a reddish patina and present columnar jointing. The contacts of the andesites with the other units are not exposed. In places the weathering is advanced and the rock crumbles easily before a hammer. Fresh andesites are observed where they have been exploited in a quarry. These rocks would be an excellent foundational material.

Lacustrine: Lacustrine deposits are of unknown age, but there are indications that these materials were deposited in the Pleistocene and are probably correlative with lacustrine deposits observed by Dobrovolny, *et al.* (1963) near Puerto Montt.

Lacustrine deposits although hidden by talus in many sectors are observed in numerous steep localities at the edge of the sea, especially in banks in the low and intermediate terraces.

The lacustrine deposits are clay and fine silts, gray and chestnut yellow to reddish in color, plastic, compacted and consolidated with almost horizontal stratification, having very fine varve-like laminae of a few millimeters thickness. Certain levels contain thin beds of hard, reddish laminae with cross-bedding oriented north 20°east; in some levels it is somewhat sandy with a few 10-cm boulders. The boulders are in general hardened clay. Much of the bedded clay is delicately folded by syngenetic deformation. The lower contacts of the clays and silts have not been observed. Nevertheless, it is possible that on the western bank of the Rio Gamboa the sediments are angularly discordant over metamorphic rocks. Sands and gravels of the fluvioglacial deposits are concordant with the clays; lacustrine deposits are not weathered.

Fluvioglacial Deposits: The fluvioglacial deposits of Castro are probably of Pleistocene age. They are distributed in terraces and elevated plains. The fluvioglacial deposits have furnished a large part of the materials deposited over the slopes.

The morphology of the fluvioglacial deposits is very distinct. The materials are deeply eroded in the form of great plain steps, or terraces, that have, in general, a similar lithological composition. Materials found in a road cut are listed in table 1.

Slope Deposits: With the exception of the terraces, the major part of the zone studied has slopes that vary from moderate to strong, covered almost completely by diverse materials, colluvium, landslides, etc, that have been grouped in one unit. The Recent slope materials have various common characteristics: (1) The constituent clasts are unsorted; rather, the relationships between individual clasts, such as grains, particles, boulders, etc., are chaotic. (2) Stratification is indefinite or not observed. (3) The clasts are uncemented. The material is a loose aggregate without compaction or hardness. (4) The materials of these deposits come from rocks and sediments emplaced in and above those on the slopes, transported by slope wash and mass movement. (6) The materials are deposited and displaced intermittently (they cover most of the slopes, partially hiding the formation or rock units that are older). (7) Where vegetation is abundant, displacements diminish. The inclination of the materials varies, in accordance with the topography, the angle of repose. (8) The material is easily displaced in a downslope direction by soil creep, mass movement, rapid sliding, etc., motivated by movements of scant energy, erosion at the base of the slopes, modifications of the slopes by the works of man, etc.

TABLE 1

MATERIALS IN SECTION OF ROAD BETWEEN THE EXTREME SOUTH OF ESMERALDA STREET AND THE RIO GAMBOA BRIDGE

Material	Thickness (meters)	Epoch
Humus soil, dark gray	0.50	Recent
A thick to fine sand with gravels having boulders of more than 25 cm and of yellowish gray color; poorly classified. The phenoclasts are angular to rounded and polygonal; those of metamorphic rocks and andesites predominate. The sediments are not cemented; they come apart easily with hammer blows. The stratification is not well defined, and in many parts stratification of a torrential type is observed. Lenses and beds of clay-like sands about 20 cm, but of small horizontal extent, are noted	20.00	Pleistocene (fluvioglacial deposits)
Clays and silts of Lacustrine origin very much covered by slope deposits	20.00	Pleistocene of Lake deposits

Beach Deposits: The beach deposits are distributed along the estuary of Rio Gamboa, of Castro Fiord, and of the bay or estuary to the east of Castro. The deposits of the two estuaries derive, in part, from mass wasting but principally from sediment transported by the rivers to the east of Castro and deposited in a delta. Although wave action is slight the materials of the deltas are probably moved by the waves on the beach during high tides, producing better sorted clasts than those of the deltas. The beach deposits are largely disaggregated silts and gravels.

Alluvial Deposits: Alluvial deposits are distributed along the course of Rio Gamboa, a little to the north of the landing field and in the deltas that are in formation in the estuaries, and to the north of Castro. In Rio Gamboa the alluvium occupies the banks, especially in the curve a little to the north of the bridge. The alluvium has a very scant development and is covered by water at high tide. The deposits of alluvium that are forming the deltas, are observed in the estuary of Rio Gamboa during low tide. The alluvial deposits are unconsolidated sediments whose clasts may vary between clay and boulders.

Deposits of Artificial Fill: The deposits of artificial fill are distributed on the banks east of Castro from Calle Thompson to the Avenida Pedro Montt, on the footings of the bridge over Rio Gamboa, and in small urban sections.

The materials of these deposits are gravel, sands, bricks, wood, and garbage, etc., which form a loose aggregate, neither compacted nor strong. The artificial fill has been utilized to modify some sectors of the bridge and the vicinity around the dock. Good sections of these deposits were not observed, and the thickness is unknown even though it is presumed to reach between 3 and 4 meters as a maximum. It is probable that other urban areas are artificially filled. This material is totally unsuitable as a basis for construction.

Geomorphology

The most noticeable morphological elements in the area are the terraces. The three terraces, and other higher terraces outside of the area, indicate relative changes of sea level, or of the regional base level. The terraces were probably formed by fluvial erosion of fluvioglacial sediments deposited by glacial melt water in the Pleistocene Epoch. It is possible that over the terrace surfaces there may be other fluvial sediments that have not been distinguished from the older fluvioglacial deposits. The present rivers of the zone, among them the Gamboa and its affluents, are actively deepening their beds.

Characteristics of the Earthquake

The movement, according to the people interrogated, was at first smooth, but soon transformed into a brusque movement that made it difficult to remain on foot. Some people were certain that they heard subterranean noises. There was no accord as to direction of the movement.

The authors estimate that the intensity of the earthquake in Castro was Mercalli VIII, based on the damage suffered by different structures. On some steep slopes the intensity reached Mercalli X.

Characteristics of the Maremoto (Tsunami)

The tsunami of 22 May 1960 was observed in Castro. The level of the sea climbed and went down over ranges notoriously higher and lower than the high and low tides of any epoch of the year. The water rose three times within 7 hours. The advance over the coast was relatively slow and did not have the violent characteristics of a *golpe de agua.* The more notable lowerings were recorded at approximately 1600 and 1730 local time on the 22nd of May.

It is difficult to estimate the maximum height of the water during the tidal wave with respect to the average level of the sea before the earthquake. In two buildings near the dock were marks left by the level of the sea. The authors observed that the difference between the high tide of the 10th June 1960, and the highest mark of the advance of the sea during the tidal wave is approximately 1 meter. The measuring with respect to the conditions before the earthquake is complicated by not knowing exactly the vertical distance that the water front was sunk by effects of the earthquake. This vertical distance was estimated a few days after the earthquake to be about 2.1 meters, according to a report from the governor of Castro, Sr. Osvaldo Barrientos, to the Minister of the Interior. The vertical distance could be measured with exactitude if one had precise altimetric points. According to the villagers, the tides at present do not arrive at the same heights that they reached in the same months of previous years. For this reason the reference concerning the maximum altitude of the advance of the sea during the tidal wave can be made only with respect to whatever level is presently reached by the sea.

Apparently the greatest destructive results of the maremoto are on the western and northern coast of Chiloé. The authors had the opportunity of visiting Ancud for several days and Cucao very briefly. Also they flew in a FACH helicopter over the west coast and southern part of the island. In all these localities, the effects of the tidal waves have been incomparably more destructive than in Castro.

The authors believe that future earthquakes with submarine epicenters in the canals east of Castro may produce destructive waves. The position of Castro inside a fiord sheltered from the open sea may not reduce the effects of these tsunamis. On the contrary, the destructive effects of these marine waves in the closed bays may be accentuated. This hypothesis should be taken into account in planning construction on the coast of the fiord.

EXPRESSION OF THE EARTHQUAKES IN THE MORPHOLOGY

Mud Volcanoes: According to the verbal information of the governor of Castro, Sr. Osvaldo Barrientos, the earthquake of the 22nd of May produced small mud volcanoes in the modern deposits on the coast of the fiord of Castro.

Movement of Materials at the Bottom of the Bay: According to information from the same source, a movement of material in the deposits in the bottom of the fiord took place. Some of the villagers who took to their boats, fleeing the effects of the earthquakes, informed the authors that during their stay on the sea they smelled a strong odor of decomposed material. The authors attribute this odor to methane gas arising from decomposition of organic material in the bottom sediments.

Compaction of Artificial Fill: The compaction of artificial fill was manifested by vertical displacements along lines of fractures, and in some cases displacements by lateral pressure. In Castro, artificial fill is observed along the Calles Lillo and Pedro Montt from Calle Thompson toward the beginning of the highway to Ancud. In part, the surface presents only open fractures and, in other places, vertical displacements of about 40 cm along the fractures.

The major destruction by compaction was the dock at Castro, which was totally destroyed by the displacement of bits of rocks, sands, and gravel, which served as a base for the concrete that formed the foundation of the dock. The sea wall between the dock and a point about 200 meters from Calle Thompson gave way from lateral pressure caused by compaction and fell into the sea.

Landslides in Steep Areas: In the steep colluvium-covered slopes between the different terrace levels, material has been displaced along fractures with a vertical displacement of about a meter and a half. The material consists principally of unconsolidated gravels and sands. Some sliding of clay was observed where the slope was between 75 to 90 degrees. The most spectacular sliding occurred at the southern edge of the city. A road that ran about 20 meters below the present road to the airport suffered from sliding, and a large part thereof disappeared below the materials that slid from the higher zones, leaving only small fragments exposed to view. If the soil had been saturated as it generally is in times of great rains, the sliding of the poorly consolidated materials would certainly have been converted into very destructive torrents of mud.

Relation Between Geology and Damages

General Aspects: The works constructed by man are seated over five of the eight recognized geologic units. This commentary will concern itself with the relationship between the damages and the materials of these five formations, taken in order from the oldest to the newest. The relation between the damage and the materials is complicated by the topography, which in Castro is a factor of major importance. The damage to construction on the terraces is notoriousy less grave than the damage produced in any of the other topographic forms, slopes, low zones, etc.

Metamorphic Rocks: The dam of the Rio Gamboa is over the well-consolidated metamorphic rocks. The works have not suffered damage. The authors do not know whether or not the undamaged bridge over the Rio Gamboa is seated upon metamorphic rocks, however, these rocks outcrop near the bridge and on the western bank, and it is presumed that in the river to the east they are at shallow depth.

Fluvioglacial Deposits: A great part of the buildings in the city of Castro and the landing field are constructed over the intermediate terraces.

It is observed that the damage in the terraced levels of the fluvioglacial deposits is considerably less than in other sectors of the urban area. In the terraces where the majority of the edifices are of wood and of one story, great part of the damage was caused by bad construction and by old age. The plan of the damage, made by the Institute of Housing, Urbanism, and Planning of the University of Chile, brought out the following: of the 32 houses situated in the block east of the Calle Carrera, between Arturo Pratt and Gabriela Mistral, 2 were totally destroyed, 10 had grave but reparable damage, 7 had light damage, and 13 were not damaged.

The damage was greater at the edge of the terraces than in the central part, as may be deduced from the following figures: Of the 14 houses situated in the block southwest of Calle Portales, between Eyzaguirre and Carrera, 4 were totaly destroyed, 2 had irreparable damage, 7 had severe reparable damage, and 1 had some light damage.

Beach Deposits: The authors observed that the houses constructed over piles on the beach deposits and along the edges of Avenida Pedro Montt resisted well the effects of the earthquake. The houses are mostly old and are constructed completely of wood. Only a few houses were destroyed because of breaking of the pillars, or because they were displaced from their foundations for lack of adequate fastenings. The sea wall on Calle Lillo is probably constructed over these deposits. The fact that it was destroyed is not a valid argument to establish the weakness of the material on which it was constructed, since apparently it was not designed to resist the lateral pressure of the artificial fill it was intended to retain.

Slope Deposits: The buildings situated on slope deposits are in general very much damaged and many are completely destroyed. The damage was due in general to two principal facts: (1) sliding of the edifice and of its foundations by inclination or separation of foundations, and (2) sliding of the terrane on which the building was situated. That the damage to structure on deposits along the slopes has been more considerable than in other urban sectors, such as terrace deposits, etc., is shown by the following figures: Of 18 houses on the northern part of the Calle Blanco, 8 were completely destroyed, 6 had serious, reparable damage, 1 had light damage, and 3 had not suffered damage.

TABLE 2

Damage as a Function of Locality & Subsoil

Type of Deposit	Total Houses	Not Damaged	Damaged			
			Total	Serious Irreparable	Serious Reparable	Light
Slope (Calle Blanco, north side)	18	3	8	—	6	1
Fluvioglacial (intermediate terrace, Calle Carrera, east side)	32	13	2	—	10	7
Fluvioglacial (edge, of intermediate, terrace, Calle Portales, southwest side)	14	—	4	2	7	1

Deposits of Artificial Fill

The buildings and structures situated on deposits of artificial fill were catastrophically damaged by the earthquakes. The greatest damage was brought about by compaction, which produced shear forces in the buildings, and by sliding and fracturing of the artificial fill. The most conspicuous damage in the artificial fill was observed in the totally destroyed dock.

Summary of Damage

The damage, in accordance with the partial examination made by the authors of figures of the Institute of Housing, Urbanism, and Planning of the University of Chile, has been summarized in table 2.

Conclusions

The authors have observed that there is a direct and clear relation between the geology of Castro and the damage of the works constructed by man.

The most considerable damage is concentrated in the constructions situated over deposits of artificial fill and slopes composed of hybrid, friable material that is neither classified nor consolidated.

The highest part of Castro, built over terraced glaciofluvial deposits, suffered comparatively minor damage. This is attributed more to the almost horizontal position of the terraces than to the quality of the fluvioglacial deposits as a foundation material. The fluvioglacial deposits are composed of uncemented sediments that are easily disaggregated and that slide easily on steep slopes. Use of wood in construction contributed to lessening the damage caused by the earthquake.

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RELATION BETWEEN THE GEOLOGY AND THE EFFECTS OF THE EARTHQUAKES OF MAY 1960 IN THE CITY OF ANCUD AND VICINITY, CHILOÉ

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(Translated and Abridged by Pierre Saint-Amand)

ABSTRACT

The rocks and sediments of Ancud and suburbs have been grouped into five units. The volcanic rocks are included in a unit, or geologic formation, called the Volcanic Complex of Ancud. The complex is tentatively considered to be Tertiary or Quaternary in age and is formed of andesites, welded tuffs, breccias and agglomerates that outcrop in almost all the hilly region, the coast, and the surroundings of Ancud. In some sections terraces have been formed over the rocks of this complex. The outcrops of the complex are weathered to a reddish-yellow material easily disaggregated with a hammer. Terrace deposits are observed in some of these terraces to be poorly cemented gravel, clay, and limonite. The alluvial deposits are distributed in the stream courses of Rio Pudeto and in Matadero and La Toma Creeks; they are composed of unconsolidated gravels, sands, silts, and clays. Beach deposits are observed along the length of the coast, and are principally a poorly consolidated aggregate of gravels and sands. Artificial fill is deposited in the coastal zone; its materials are gravels, sands, silts, bricks, wood, debris, etc.

There is a relation between the geology and the damage produced by the earthquakes in works of man. The areas underlain by the Volcanic Complex of Ancud are those that best resisted the effects of the earthquakes, and these are suggested as the most suitable for the expansion of the city. The most serious damage from the earthquakes are observed over the alluvial deposits and at the edges of one of the terraces. The last observation suggests that these areas are unfavorable, and that any future plans for construction over these should be preceded by a study of soil mechanics. It is indicated that the geographic position of Ancud with respect to tidal waves is unfavorable. It is suggested that the construction be prohibited near the sea, and that absolutely indispensible coastal buildings should be carefully studied with regard to a possible repetition of the phenomena.

Introduction

Location of the Zone and Purpose of the Study

Ancud, capital of the province of Chiloé, is located in the extreme north of the big island, at 41°52′S. latitude 73°49′W. longitude. Ancud has an urban population of 6,396 (census of 1952 by the General Direction of the Statistics and Census) and covers an area of about 1½ sq kilometers. The principal industries are agriculture, livestock raising, fishing, and lumber. It is accessible from continental Chile by air and water. The most important roads are highways to Castro, Chacao, and Quetalmahue. The road to Chacao was cut when Pudeto bridge was destroyed by the earthquake and the sea wave. A narrow-gage railroad, uniting Ancud with Castro was paralyzed because of the earthquake. Figure 1 shows these localities.

The object of the present study was to collect all available geologic information concerning Ancud and its surroundings and to establish the relations between the damage produced by the earthquakes and the quality of the ground that underlies the city. A preliminary geologic map of the urban areas and of the possible extension of the town was made. The work was done during August and September 1960.

The best topographic map available is inadequate for the required precision of the work and contains grave errors, principally of altitude. This map, with an original scale of 1:2,000, is the *plan-regulador* de *Ancud*, upon which we have indicated the different lithologic and morphologic units observed in the terrain (figure 2).

Relief and Drainage

The zone studied consists principally of the two ranges of low hills that run in an east-west direction, separated by the shallow quebrada of La Toma Creek. These hills at the shoreline, present an undulating landscape of low relief. They begin in the vicinity of Rio Pudeto and rise to a height of 70 or 80 meters. They descend smoothly to the north and terminate in the bay of Ancud in a bank 8 to 10 meters in height. A great part of the zone studied is drained by the little creeks of Matadero and La Toma. Matadero rises in numerous small springs and runs in a westerly direction, reaching the sea after about 1½ kilometers. La Toma begins approximately 1 kilometer east-northeast of the Plaza of Ancud. In its lower course, where it crosses the city, it has been put into canals, debouching near the dock of Ancud.

GEOLOGY

Rocks of the Volcanic Complex of Ancud

In the region of Ancud, volcanic rocks crop out that have tentatively been included in a unit, designated the Volcanic Complex of Ancud, which cannot be described here in accordance with accepted stratigraphic norms owing to a lack of field information such as the stratigraphic relations, type section, etc. The age of the Volcanic Complex is unknown. Felsch (1913, p. 98) suggests a Tertiary age. On the geologic map of Chile, IIG 1960, the volcanic rocks of the north of the island of Chiloé are shown as "Quaternary and in part Tertiary, basaltic, volcanic rocks and andesites, in part intrusives." The authors, for lack of other arguments, lean toward an age of Tertiary-Quaternary. The rocks of the Volcanic Complex vary in lithology, but on the map they are indicated by a common symbol. It is presumed that these volcanic rocks—even where covered by alluvium, beach deposits, artificial fill, or organic soil—underlie Ancud and vicinity to unknown depths.

Morphology

The volcanic rocks form a landscape of smoothly rounded hills. In some parts, where the sea has cut terraces, the rocks are sub-horizontal. These terraces have been subsequently disected by superficial waters. The rounding of the forms of the countryside is attributed to prolonged erosion that has worn away the once irregular original forms of a volcanic field. The rock is now deeply weathered and an organic soil is well developed. The volcanic rocks form slopes at the coast as steep as 90°.

Lithology

In some localities the Volcanic Complex of Ancud is composed of a dark-gray, jointed, compacted, massive andesite that is resistant to blows of a hammer. Under the microscope an intergranular texture is observed, with individual crystals of clinopyroxene and magnetite. The interstices between the plagioclase crystals are filled with chlorite. Near the fair grounds of the Agricultural Society of Chiloé, the andesites are vesicular. In part, the vesicules are filled with some clear secondary minerals. The presence of vesicules suggests that the andesites were laid down as beds of lava in some parts of the region.

Some 300 meters east of the shooting club building, destroyed by the maremoto, are welded tuffs. These are rocks of a marked eutaxic texture—light gray and dark gray, with a great deal of glass and xenoliths. They ring to the blow of a hammer, are well lithified with scarcely noticeable vertical joints, with holes up to about 20 centimeters in length parallel to the eutaxic texture, presumably left by gases, flattened during the cooling of the pyroclastic layer. These welded tuffs are reminiscent of the formation Altos de Pica in Tarapaca (Galli and Dingman, 1961).

A third collection recognizable among the volcanic rocks of this complex is composed of agglomeratic breccias formed by blocks of several cubic meters, enclosed in a pyroclastic matrix of lapilli between 32 and 4 millimeters and other pyroclasts less than 4 millimeters. The blocks are of volcanic origin; some of them are vesicular lavas and welded tuffs. This circumstance suggests that the agglomeratic breccias are somewhat more recent than the lavas and tuffs. The agglomeratic breccias are not stratified, and the pyroclastic fragments are not lined up or classified, but are distributed chaotically; nevertheless, in a locality on the coast some 1,000 meters to the north of Caleta Pudeto, and in another site, southeast of the mouth of the Estero Matadero, the breccias are poorly stratified. In the first of these localities is a synclinal structure with an approximately east-west axis. In the second location, the strike of the beds is approximately northeast and the inclination is 20° to the northeast. This indicates that the Volcanic Complex of Ancud has been in part folded by tectonic movements.

Weathering

Unaltered volcanic rocks are seen along the coast where the sea is actively eroding them and carrying away the loose material. In other localities, almost without exception, the volcanic rocks are weathered to a depth of about 15 meters. The weathered beds are composed of a light-reddish-yellow claylike material of variable thickness, easily broken with a hammer. The clay materials presumably come from decomposed plagioclase in the andesite. It is possible that in other parts, such as the future industrial zone of Ancud, the subsoil is similar.

Terrace Deposits

Several partially dissected sub-horizontal areas near Ancud are the remains of sea-cut terraces and possibly also river terraces. The terraces indicate that in the geologic past, the level of the sea was considerably higher with respect to the present topography in the zone studied. It is possible that some terraces elaborated by the erosive and cumulative action of the rivers are in part covered with alluvial deposits.

In general the terraces are not covered by sediments of great thickness. Some terraces exhibit features that suggest that extensive areas of the rocks of the Volcanic Complex of Ancud, lie under a vegetable soil at the shallow depth of 1 to 3 meters. These sub-horizontal levels dissected and modulated by the erosion of superficial waters, are indicated on the map by approximate limits because of their great interest to architects and engineers in charge of the location of new suburbs.

In the cliff situated behind the Intendencia of Ancud, the section is composed in part of terrace sediments, as follows:

	Thickness (meters)
1. Vegetable soil	0.30
2. Yellow chestnut gravel with sandy-clay matrix poorly cemented, easily disaggregated with the hammer, with rounded boulders and rocks of diverse origin and with layers of reddish limonite	2
3. Material similar to the aforementioned, but reddish clayey cemented limonite. This bed is hard and offers resistance to the blow of a hammer. In the cliff the bed has a constant thickness and may extend beneath the building	0.50
4. Clayey materials, somewhat sandy, well compacted with some boulders	6
5. Talus	?
6. About 15 meters of reddish yellow clay derived from decomposition of the volcanic rocks overlies the volcanic rocks	--

Alluvial Deposits

The alluvial deposits are distributed principally on the east of the zone along the margins of Rio Pudeto. In Ancud the Matadero and La Toma Creeks have alluvial plains of small extent. The morphology of the alluvial deposits is subhorizontal and regular. The deposits are composed of gravel, sands, and mixed clay and silts that have been transported and laid down by river waters. The deposits are of Recent age, neither cemented nor compacted.

Beach Deposits

Beach deposits of unknown thickness, distributed along the coast, are composed principally of unconsolidated aggregates of gravel and sand. These derive in part from local rocks, eroded and removed by the waves, and in part from sediments transported by the waves and marine currents from zones far from Ancud.

Deposits of Artificial Fill

These deposits were made to flatten the coastal zone extending from some 300 meters to the north of the Customhouse to the neighborhood of the mouth of Estero Matadero, where numerous houses were subsequently constructed. Most of these houses were destroyed by the maremoto of 22 May 1960. The maremoto and the later motion of the talus have left this area completely unoccupied. This fill was made with gravel, sand, silt, bricks, wood, trash, etc. The maximum thickness of the deposits of artificial fill is unknown, but it is probably some 3 meters.

Sr. Erwin Wolf informed us verbally that parts of the landing field have been artificially filled to a depth of 6 or 7 meters on the swampy Recent flood plain in the Rio Pudeto. Other artificially filled areas may exist within the city limits of Ancud.

CHARACTERISTICS OF THE EARTHQUAKES

At 1510 on the 22nd of May an earthquake classifiable as a Terremoto was noted in the city of Ancud. According to 23 people interrogated, the movement began at 1500 hours in a smooth gentle manner, continuing thus for more than 10 minutes. It then turned into a movement of great violence. This circumstance permitted the major part of the population to abandon their houses in time to reach places of comparative safety.

Eight of the people interrogated declared they had heard subterranean noises. There was no unanimity of opinion with respect to the direction of movement; this suggests that the movements could have been oscillatory. The authors have estimated that the intensity reached MM-IX in the most strongly affected parts of Ancud, on the basis of observations of damage in the field and of information from people regarding the effects observed during the earthquake.

Characteristics of the Maremoto (Tsunami)

The maremoto generated by the earthquakes of 22 May 1960 caused catastrophic destruction along the coast of Ancud and other parts of the south of Chile. According to Sr. Erwin Wolf, who witnessed the phenomenon, the first rising of the sea was not preceded by a retreat of the waters. The sea rose slowly for approximately 18 minutes after the earthquake, until it reached some 80 centimeterers above the lower part of the part of the door of Sr. Wolf's house in Calle Quintanilla. The surface of Calle Quintanilla, which was removed by the effects of the maremoto, was not covered by marine waters previously, not even at the highest tides. Minutes later the sea retired rapidly, for some 5 minutes. The current toward the sea tore away wooden houses that were situated on beach deposits after previously having been floated away from their light foundations.

The arrival of the second wave was preceded by a lowering that reached a level considered normal. The water advanced slowly until it covered all of the door of the entrance of Sr. Wolf's house, approximately 2 meters above Quintanilla St. Upon retreating again with great force, the water tore it and other wooden houses seaward.

The arrival of the third wave was preceded by the retreat of the waters as far as the center of the bay of Ancud. Isla Cochino, to the north of the peninsula of Ancud was temporarily united with the continent. The inhabitants contemplated in an astonished manner a phenomenon never seen before. The noise was deafening and was probably caused by the tearing up of the stones and by the whirlpools and turbulence of the water. The bottom of the bay was exposed to view. It was observed to be relatively flat, covered with sand and green algaes and some outcrops of rocks. Strong whirlpools were observed at the edge of the water but were concentrated in the center of the bay.

The advance of the water from the center of the bay until it arrived at the coast of Ancud required some 15 minutes. At first a wave several meters in height was observed. Upon arriving at the vicinity of the dock, the water advanced as a great tide rather than as a wave, but the force of impact of the water was phenomenal. The water advanced from the north of the coast toward the future industrial zone in an enveloping movement, then swept over the coast and retreated toward the north, taking in its path hundreds of houses and destroying other structures. The maximum height reached by the water over the beach of the future industrial zone was 6 or 7 meters.

MORPHOLOGICAL EXPRESSIONS OF THE EARTHQUAKE

General Sinking of the Zone

According to Sr. Ulises Correa, engineer of the Corporation de Fometo de la Produccion in the Estacion Ostricultura de Pullinque, situated in the north of the gulf of Cape Quetalmahue, the coast sank 1.8 meters. The measurements were made on a dock situated over cemented sands locally known as *cancagua.* This suggests that the sinking of this part of the coast is not owing to compaction of poorly consolidated sediments but to a general descent of the zone, probably by faulting.

These observations are in accord with others made by the authors immediately to the north of Ancud, near the destroyed gun club. Before the earthquakes, a building had been situated here upon the volcanic rocks, which is the principal andesitic lava, out of reach of the tides. As a result of the earthquake these installations were destroyed, leaving only the concrete foundations lying directly over the volcanic rock. These foundations are now in part covered by the high tide. The authors were not able to determine the amount of sinking because of a lack of reference point.

Compaction of Alluvium

The alluvial sediments deposited by Rio Pudeto in Recent geologic time have suffered a strong compaction owing to the earthquakes. Before the earthquakes, the bridge over Rio Pudeto had its extremities situated on both shores of the principal branch of the river, out of reach of the water. The western extremity was situated over a little island of Recent sediments, surrounded by two arms of the Pudeto, of which the western arm was small, narrow and of no great flow, while the eastern or principal arm was wider and of great flow. The extreme eastern part of the bridge was situated over a bar in the mount of Rio Pudeto. Over the western arm of the Pudeto there had been constructed a terraplain of artificial fill. As a consequence of the earthquakes the little island disappeared beneath the waters. Today it is a zone of shallow water, from which emerge remains of the terraplain and of the road in the higher parts of the island. The two arms of the Pudeto are now united, and the river now forms a single channel. The authors suggest that because they are modern sediments without consolidation, the sinking of the island was produced by compaction of the alluvium, added to the general sinking of the zone as demonstrated to the north of Ancud.

Fractures

In the Ancud area fractures caused by the earthquakes are observed only in very narrow zones in modern sediments. In the airport of Pudeto there are cracks 2 or 3 centimeters in width and up to about 10 meters in length running parallel to the river. These are lurch cracks, deriving from small landslides without much vertical displacement that have carried the alluvium toward the river.

Sr. Wolf informed us that in the Calle Arturo Prat, constructed over the alluvial sediments of the La Toma Creek, there were cracks some 40 centimeters in width, and that cracks of about 50 centimeters in width were observed in the road to the airport in Pudeto. Cracks of lesser size were found in the weathered volcanic rocks between the Caleta Pudeto and Ancud.

Relation Between Geology and Damages—General Aspects

A relation between earthquake damage to the works of man and the soil conditions is clearly demonstrated in Ancud and environs. This must be considered in reconstruction plans.

The effects of the maremotos were so severe that the authors were not able to estimate damage produced by the earthquake on the beach deposits and the artificial fill distributed along the coast. The brief commentary concerning the relation of the geology and the damage will be limited to three units that were affected only partially by the maremoto—the volcanic rocks, the terraces, and the alluvial deposits.

According to the account of Sr. Wolf, the coastal zone of Ancud did not suffer serious damage derived exclusively from the earthquake. Nevertheless, he observed that cracks were formed in the coast by the effects of the earthquake. The cracks and the force of the ground movement must have affected many houses along the coast, especially those constructed of bricks and other heavy materials—the effects of the earthquake being eradicated only minutes later by the phenomenal advances of the sea.

Damages in Volcanic Rock

In spite of the thick weathered bed that overlays the rock of the volcanic complex of Ancud, the volcanic rocks are the best material in the zone for building purposes. Fortunately, almost all of Ancud and the possible zones for future expansion are located over these rocks. The damage observed over this unit is not serious, overall, if it is compared with the damage in the alluvial deposits on the edges of the terraces. Even on somewhat steep slopes the volcanic terrain failed in very few places, or was not observed to be cracked.

Without reservation it may be concluded that the rocks in the volcanic complex of Ancud, in areas of little or no slope are excellent foundation materials.

Damage on the Terraces

In the terraces the damage of the earthquake is observed mostly at the edges. The front of the white house indicates Calle Pudeto and the border or edge that failed. Many houses situated on the northern side of Calle Pudeto, along the edge of the terrace, were seriously damaged or completely destroyed—mostly between Calle Las Heras and the Plaza de Armas. Shaking of the earthquake cracked the edge of this terrace, and it slid down into La Toma Creek. This phenomenon was in part the cause of the great destruction. On the eastern edge of the terrace the cathedral and the Intendencia were severely damaged. The Intendencia is located over the terrace sediments already described. Increase of this damage towards the edges of the terrace is another geologic aspect related to the damage that should be considered in the reconstruction. In the dissected terrace of the future industrial region there are neither cracks nor landslides.

Damages in Alluvial Deposits

The houses over the Calles Dieciocho and Pratt, between the Ancud-Castro railway station and Calle Libertad, are constructed over alluvial deposits. The number of houses destroyed and partially destroyed by the earthquake is only comparable along the northern edge of Calle Pudeto. The destruction of Calles Dieciocho and Pratt indicates that the alluvial deposits are very poor foundation materials. The destruction has been clearly more intense in the alluvium than in the areas of volcanic rock.

CONCLUSIONS

In Ancud and thereabouts, very clear relations were observed between the damage produced by the earthquake and the characteristics of the rocks and sediments of the region.

The most important damage occurred over the alluvial deposits and the border of one of the terraces. On artificial fill and beach deposits one cannot observe damage produced by the earthquake because the maremoto destroyed the coastal zone.

The zones formed by the rocks and the Volcanic Complex of Ancud (with the subhorizontal topography) are those which best resist the effects of the terremoto.

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EFFECTS OF THE EARTHQUAKES OF MAY 1960 IN CONCEPCIÓN AND VICINITY

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(Translated and Abridged by Pierre Saint-Amand)

ABSTRACT

The rocks and sediments of the region have been divided into four units: metamorphic rocks of unknown but great age; granites of Jurassic-Cretaceous age; fossiliferous sediments of Cretaceous and Tertiary age; Quaternary sands, silts, clays, gravels, and artificial fill. The metamorphic and intrusive rocks are deeply weathered.

In general, damage is clearly related to the type of materials of construction, independently of the subsoil. Nonetheless, damage was over soft alluvium and artificial fill. The overpass on the north of the railway bridge on Rio Bio Bio sunk into artificial fill and was damaged. The houses that survived best were built of reinforced concrete or wood. Houses of adobe or bricks held together with poor mortar or mud failed miserably. In the steeper zones, danger from landslides menaces populous areas in the hills La Pólvora, Chepe, Chacabuco, and others.

INTRODUCTION

Location of the Zone Studied and Purposes of the Study

The zone studied, an area of about 400 km^2, is located in the province of Concepción, between parallels 36°35′ and 36°50′, south latitude, and meridans 72°57′ and 73°15′, west longitude. This includes portion of the departments of Concepción, Coronel, and Talcahuano. It includes the cities of Concepción, Talcahuano, and Penco.

The purpose of this study was to collect as much information as possible on the relation between the seismic damage and the quality of the terrane in the regions affected by the earthquakes of May 1960. The work consisted principally of geologic mapping of the zone, giving special attention to some areas, such as Concepción and its immediate vicinity.

The topographic base used were maps on a scale of 1:25,000, of the Instituto Geografico Militar, upon which were indicated lithologic units, their contacts and structural relations, the locations of some wells, rock slides, etc. Vertical air photos of the zones were used in the interpretation.

In the city of Concepción, a house-by-house census of damage was made, recording the types of damage, the material and type of construction, and the quality of the terrane. Damage was examined in the plant of the Compania de Acero del Pacifico (Huachipato) and in the sugar refinery at Penco.

The level of the water in several wells in Concepción was measured, with the intention of estimating the phreatic level. For a later, more detailed study, samples were taken of the rock, sediments, and water, to be examined in the laboratory. Abundant fossiliferous material was collected to determine the regional stratigraphic sequence. Because of the preliminary character of the present report, the stratigraphic considerations herein are very brief.

Relief and Drainage: Three well-defined morphologic units are distinguished in the regional relief (figure 1 in pocket at the back of this issue): the hills immediately to the east of Concepción and Penco, an alluvial plain between Concepción and Talcahuano, and the hills of the peninsulas of Las Tumbes and Tetas.

The hills to the east are low, undulating, and constituted of well-consolidated rocks. South of the Rio Bio Bio they form the foothills of Cordillera de Nahuelbuta.

The alluvial plain is limited in the south by the lower course of the Rio Bio Bio in the east by the cities of Concepción and Penco, in the west by the Pacific Ocean and the mountainous areas of the peninsulas of Las Tumbes and Tetas. The most noticeable irregularities are some low terraces and a few hills of sedimentary rock, the largest of which is Cerro San Miguel.

The peninsula of Las Tumbes is 12 km long and 3 km wide. Its maximum altitude is 254 meters, 2 km west of Talcahuano. The peninsula of the Tetas hills has a maximum altitude of 260 meters. Both peninsulas are constituted of granite or metamorphic rocks. The seaward coasts are irregular and abrupt.

The bay of Concepción has a low reactilinear coastline covered with sand dunes between the mouth of Rio Andalien and Talcahuano. The bay of San Vicente lies between the peninsula of Las Tumbes and the Tetas hills.

The principal hydrographic system of the region is Rio Bio Bio, which drains some 23,920 km^2.

Rio Andalien rises in the eastern hills and runs, in its upper and middle courses, toward the west until Concepción, where it is deflected to the north, to discharge into a wide estuary near Penco. The short Rio Lengas runs about 6 km from its source in the meadows, Las Higueras, to its mouth in the bay of San Vicente.

GEOLOGY

Undifferentiated Metamorphic Rocks

The age of these is unknown but may be pre-Cambrian to Upper Paleozoic. The oldest rock of known age in the region is of Cretaceous age and is unmetamorphized. Unmetamorphized Triassic rocks are found in a nearby area.

Distribution: Metamorphic rocks are exposed in the peninsula of Las Tumbes; in the peninsula of Tetas, in the hills Tetas Norte and Tetas Sur; and on the left bank of the Rio Bio Bio.

Morphology: The metamorphic rocks, in general, form the highest hills. In the central and highest parts of the peninsula of Las Tumbes and the Tetas hills, the morphology consists of a chain of long low hills. On the eastern and western edges of the peninsula, the relief is broken by the numerous V-shaped valleys of steep gradient. The divides between these valleys are relatively flat, worn by marine abrasion, and constitute a very conspicuous terraced level.

To the south of Concepción, metamorphic rocks are shown on the geologic map of Chile (Instituto de Investigacíones Geologicas, 1960) as the principal constituents of the hills between the western bank of the Rio Bio Bio and the coast. The western slope of these hills have marine terraces.

Lithology: The metamorphic rocks in the region are principally a green mica schist with some metaquartzites. Microscopically, they appear to be composed of muscovite and plagioclase. Dark crystals, probably of garnet, are observed. There is a well-marked schistocity that separates very thin lamina of a silky aspect. The metamorphic rocks are intruded in all the localities by quartz veins.

Contacts: Angular discordances are observed between the metamorphic rocks and superjacent sedimentary rocks of Cretaceous-Tertiary age in the extreme south of the Peninsula of Las Tumbes, and between the metamorphic rocks, and the superficial deposits in numerous localities.

Intrusive contacts are observed between the metamorphic rocks and bodies of granite on the north coast of the peninsula of Tetas and west of the hill Tetas Sur. Other intrusive contacts have been observed to the south of the peninsula of Las Tumbes (Instituto de Investigacíones Geologicas, 1960) by previous geologists.

Fault contacts are suggested by geologic observations between the port of San Vicente and the naval base at Talcahuano. Toward the east of a supposed fault that should extend between these two points, there are extensive outcrops of sedimentary rocks, probably of Lower Tertiary age, with beds of coal that form low rounded hills. Toward the west, the peninsula of Las Tumbes suggests an ascending structural block composed of metamorphic rocks, covered in some localities by sedimentary rocks probably of Cretaceous age.

Weathering: Metamorphic rocks are observed to be fresh where the erosion is more recent and has removed the weathered mantel and the other overlying geologic formations. In the localities where a recent erosion is not observed, weathering of the metamorphic rocks reaches depths of approximately 30 meters. The metamorphic rocks *in situ* are altered to a reddish, clay-like, ferruginous material, and conserve, in part, unaltered quartz veins. Roots of plants penetrate the weathered mantel. The transition between the fresh metamorphic rocks, the altered rocks, and the humic soils is very gradual.

Undifferentiated Intrusive Rocks

The intrusive rocks are mostly granite. The age of the granites probably lies between Jurassic and Cretaceous.

Distribution: The granites are observed in parts of Cerros Tetas in the peninsula of Las Tumbes, in the eastern and northern edges of the city of Concepción, in the isolated hills to the north and west of the city of Concepción, (Pólvora, Chacabuco, and Chepe), along the road between Concepción and Penco and between Concepción and Chiguayante (Instituto de Investigacíones Geologicas, 1960).

Morphology: The granites participate with the other harder rocks in the construction of the high zones of the region. In the peninsula of Las Tumbes and Cerros Tetas, the granites have been eroded by the sea as were the metamorphic rocks. The most abrupt relief observed in granitic rocks is that of the terraces of Tetas Norte and Tetas Sur.

Lithology: The intrusive rocks are varieties of dark-gray granite. In some localities, there are intrusions of aplites and pegmatites. A microscopic examination of the granite in the quarry near the bay of San Vicente indicates that these consist of abundant quartz, feldspar, biotite, and other ferromagnesian minerals.

Contacts: Intrustive contacts are observed between granite and metamorphic rocks near the quarry to the north of the peninsula of the Tetas hills.

Weathering: With a few exceptions, the granites are weathered to a depth of perhaps 50 meters. The weathered mantel is composed of a natural gravel of gruss (locally called *maicillo*), formed by the original crystals more or less altered, depending on their mineralogical composition. The feldspars are largely kaolinized, whitened, and fractured, and only a few conserve their crystal form. In places they have been totally decomposed and constitute a friable clay-like material. In places individual crystals of mica are observed with the iron removed and in parts they are totally decomposed. Unaltered crystals of quartz are distributed throughout the weathered material. The roots of the vegetation have penetrated the mantel to depths of approximately 20 meters. The transition between unaltered granite, the maicillo, and humic soils is gradual.

The weathered mantel coming from the granites is well distributed over the immediate areas of the region, except in quarries and in places recently eroded. Even though it has decomposed in place, without major transport, the weathered material is similar to graywacke in texture. The mantel is easily broken up and resembles sand with a clayey matrix of recent origin. It can be easily removed by any light tool. In the hills covered by weathered granite, landslides have occurred because of the earthquakes. Erosion by water is in some places eliminating rapidly the weathered mantel. The weathered mantel has little resistance, has been caused to slide by movements of low energy, and is constantly removed by torrential waters, especially during periods of heavy rains.

Sedimentary Rocks

The sedimentary rocks of Cretaceous and Tertiary age are of both marine and continental origin.

Distribution: The sedimentary rocks of Cretaceous-Tertiary age crop out to the south of the peninsula of Las Tumbes, over metamorphic rocks; in the sector of Gualpen in the Tetas hills; in Cerro Conejo; in the hills Porton, Amarillo, and San Miguel; to the south and southwest of the Huachipato Steel Plant; in the hills David Fuentes and El Morro, of Talcahuano; between Chepe and Lago Lo Mendez; in Cerro Amarillo, in the city of Concepción; and in the hill La Polvora, to the northwest of Concepción.

Morphology: Cretaceous-Tertiary sediments constitute the major part of the low hills scattered about the plains on which Concepción, Talcahuano, and Huachipato are situated. The lithification is not very advanced and these hills erode rapidly. The hills are low and have smooth slopes. It is probable that the higher parts of these "island mountains"—thus called because they are surrounded by modern superficial deposits—are terraced by marine transgressions of past times.

Lithology: Cretaceous-Tertiary sedimentary rocks are in a major part fine to medium sandstones and in part fine to medium conglomerates with polygonal clasts. The sands are clayey in general and some beds are reddish plastic clay-stones.

In the sedimentary rocks of Cerro Conejo is a bank of coquinoid limestone with well-preserved fossils. The advanced lithification of the calcareous beds contrasts with the slight cementation of most of the sedimentary rocks of the region. The sedimentary rocks of Cerros David Fuentes and El Morro, in Talcahuano, of probable Lower Tertiary age, are fine, clay-like, green and yellow, limonitic, friable sandstone with sandy concretions. In El Morro there are fine conglomerates with beds of coal in clay-like strata.

The oldest strata are irregularly stratified, truncated, lenticular beds with conglomerates of varied origin, formed by phenoclasts of quarts, well rounded. These strata indicate a beach or a littoral marine environment, where the clasts were subjected to prolonged abrasion. The fauna contains mollusks and marine brachiopods with thick valves.

Above these basal strata the material is finer, consisting of reddish plastic mud stones and shales. The fossils indicate a littoral deposit.

The sedimentary rocks on the hills of David Fuentes and El Morro in Talcahuano and of Cerro Amarillo in Concepción are lagunal or continental. In the last two are found the fossil remains of plants; in El Morro beds of coal. The weathering of the sedimentary rocks is not very advanced, and under the humic soil these rocks are relatively fresh; weathering has proceeded only to depths of a few centimeters.

Contacts: The contacts of the Cretaceous-Tertiary sedimentary rocks and other formations are angular discordances. In various localities the contacts with the overlying beds are very regular, probably owing to the abrasion of transgressive seas. Only near the village of Lirquen is found a basal conglomerate with boulders of granite the size of a fist. Well-exposed contacts were observed in the south of the peninsula of Las Tumbes, over metamorphic rocks, and in various localities in Cerro La Polvora and in Lirquen, over granites.

Superficial Deposits

Distribution: Modern superficial deposits are distributed in the lower sectors of the area studied. Included among the superficial deposits is a regolith derived from processes of weathering and the formation of vegetable soil.

Morphology: Levees of lateral depositions of the rivers are quite noticeable. The Steel Company of the Pacific lent the authors a map, on the scale of 1:5,000, with 1 meter contour lines of an area along one of the pipelines that brings water from the Bio Bio. The topographic map indicates the presence of two parallel levees with an altitude of 6 or 8 meters above the surrounding terrane. The two levees are themselves parallel to the Bio Bio and have an asymmetrical profile with the slopes more pronounced toward the river. The width of the levees is between 215 and 400 meters.

One of the most noticeable morphologic aspects of the area is the river course that begins in the extreme southwest of the city of Concepción, borders the city on the west, afterwards crosses to the south of the hill Chacabuco, and continues toward Los Budes swamps in the bay of Talcahuano. This river course has been occupied by extraordinary floods of the Rio Bio Bio in historic times. The height of the floods has been considerable and in the river's course there is an alluvial plain, comparable to that of Rio Andalien, bordered by well-developed terraces. This bed is swampy, and in June 1960 was occupied by standing water, which in part came from the strong rains and in part from subterranean water. The presence of subterranean water draining all year near or over the level of the land is demonstrated by a swampy flora. The artificial fills (see the profiles of the wells in the suburb Pedro del Rio in table 1) have raised the banks of the Rio Bio Bio in the low suburbs immediately to the west of Cerro Chepe. These fills have detained the floods of the Rio Bio Bio for the last few decades.

Rio Andalien has constructed a flood plain from the interior of the coast hills to the bay of Talcahuano. This flood plain was occupied during the flood of June

TABLE 1

Profiles of Perforations

1.	
Number on the map	1b
Information from	Dirección de Obras Sanitarias (D.O.S.)
Location	Barrio Pedro del Rio, foot of c° Chepe in Concepción
Phreatic level	2.54 m from casing head
Lithologic profile	0–4 m—filled earth
	4–15 m—fine sand, 1st aquifer
	15–16.5 m—gray clay
	16.5–25 m—medium sand
	25–26 m—gray clay
	26–36.6 m—medium sand and shells, 3rd aquifer
2.	
Number on the map	2b
Information from	D.O.S.
Location	Barrio Pedro del Rio, Calle Perez Rosales
Phreatic level	2.29 m
Lithologic profile	0– 2 m—filled earth
	2–10 m—medium sand
	10–21 m—coarse sand
	21–25 m—coarse sand with gray clay
	25–30 m—coarse sand with gravel
3.	
Number on the map	3b
Information from	D.O.S.
Location	100 m west of well 4b
Phreatic level	1.92 m
Lithologic profile	0– 7 m—fine sand
	7– 9.20 m—gray clay
	9.20–10.60 m—medium sand aquifer
	10.60–14 m—clay with fine sand
	14–22.5 m—coarse sand with gravel, aquifer
	22.5–24.6 m—gray clay
4.	
Number on the map	4b
Information from	D.O.S.
Location	100 m from well 5b
Phreatic level	1.92 m
Lithologic profile	0– 1.20 m—humic soil
	1.20– 8 m—fine sand
	8– 9.40 m—gray clay
	9.40–10.50 m—medium sand aquifer
	10.50–13.90 m—clay with sand
	13.90–21.30 m—coarse sand with gravel, aquifer
	21.30–23.50 m—fine sand with gray clay
	23.50–24 m—medium sand
5.	
Number on the map	5b
Information from	D.O.S.
Location	In Gualpencillo near Rio Bio Bio
Phreatic level	1.80 m
Lithologic profile	0– 0.80 m—humic soil
	0.80– 7.40 m—fine sand
	7.40– 8.20 m—gray clay
	8.20–10.50 m—medium sand, aquifer
	10.50–12.60 m—gray clay
	12.60–24 m—medium and coarse sand, aquifer

TABLE 1 (*Cont.*)

6.	
Number on the map	6b
Information from	Cia. Acero del Pacifico
Location	Steel Plant
Phreatic level	—
Lithologic profile	0– 2 m —fine dark sand
	2– 7.5 m—medium dark sand with gravel
	7.5–10.5 m—fine dark sand with gravel
	10.5–19. m —fine dark sand
	19–21.5 m—fine dark sand with silt and shells
	21.5–25 m —very fine dark sand with some shells
	25–27.5 m—unconsolidated silt, sand, and some shells
	27.5–31.5 m—fine dark sand, silt, and shells
	31.5–33 m —altered rock
	33–36.5 m—consolidated rock

1960. The inhabitants of the suburbs of Chillancito were in part driven out by the invasion of waters. This zone of the city does not have the lateral defenses necessary to protect it.

Aerial photographs indicate that the floods of Rio Bio Bio in recent geologic time have taken the course toward the bay of San Vincente between the aforementioned levees and Cerro San Miguel.

Between the more recent flood plains there are higher areas of river deposition covered by well-developed humic soils. In the zone of Gualpencillo and Los Budes, south of Talcahuano, there are low swampy regions.

Between Concepción and Chiguayante are two fluvial terraces between Rio Bio Bio and its banks of granite. The road is constructed over the highest terrace.

The university district is a low zone and until recently was an uninhabited swamp. Several hydraulic works, such as a drainage canal that carries off the superficial water and an intermittent pump in a well situated by the side of the central hall of the university, have lowered the level of the surface water in this locality.

In some areas in the plain between Concepción and Talcahuano there is an accumulation of dark sands. Verde hill, situated between Laguna Redonda and the Club Hipico, is the most conspicuous of these accumulations. Another line of little dark sand hills is found some 2 km to the east of the hill El Conejo. The origin of these little hills has not been established.

Lithology: The superficial deposits are unconsolidated clays, silts, and sands. Because of the low relief of the deposits, observation can only be effected in eroded banks, in artificial dumps, or in specimens taken with drilling equipment. The Steel Company of the Pacific gave the authors profiles and a map of the wells made by the Raymond Concrete Tile Company in the terrain where the plant of Huachipato is constructed. These wells reached some 30 meters, and some enter Eocene rock according to Carlos Ruiz. The most outstanding characteristic of these profiles is the presence of black sands of medium to very fine grain with great lateral variation. In part the black sands contain silt, gravel, and unidentified shells. Ruiz considered the sediments to be marine deposition at the base and to be deltaic deposits of Rio Bio Bio in the upper part.

From the profiles available, wells at Gualpencillo reached a maximum of 51 meters. The details of the sediments crossed are those given by the drillers. In seven profiles, the sediments from 7 or 10 meters to approximately 12 or 15 meters, depending on the well, are a single horizon of gray clay. In all the wells, the sediments are mostly clayey sand, clays, and in lesser amount small gravel mixed with sand. Table 1 describes these wells.

Chiguayante is built on fluvial terraces of the Rio Bio Bio. In Calle Lord Cochrane, at the edge of the river, the subsoil is composed of sand to a depth of about 13.5 meters.

The wells, drilled to 41 meters, at Huachipato, cross fine and medium sands to about 21.5 meters and below that sands, silts, clays.

The two wells of the Direccion de Obras Sanitarios in the suburb Pedro del Rio (see table 1) east of the hill Chepe, indicate fill of a loose material to about 4 meters. Downwards the profile indicates sands and sands with intercalations of clay. The two wells reach some 30 meters and are located in the flood plain to the west of Concepción.

The zone where the University of Concepción is located used to be a swamp. According to the engineer, Fred J. Coleman, the perforations studied for the foundations of the university buildings crossed 50 meters of blue plastic clay. According to the same engineer a yellow clay is encountered under the stadium in the university district.

Pierre Saint-Amand and Robert J. Dingman in 1959 made a gravimetric profile between Cerros Porton and El Conejo, to the south of the steel plant, with the object of selecting a location to drill in search of water. The interpretation of Dingman, after rapid examination of the outcrops and of the results of the gravimetric profile, suggested the existence of a Pleistocene valley, bounded by normal faults, and now filled by sediments of the Bio Bio, and abandoned (see Saint-Amand, 1959).

In resumé, the low regions are filled with unconsolidated Recent deposits. The origin is in the major part continental; the sediments were deposited largely by water in swamps, river deltas, and along river courses. The common characteristic is a predominance of sands. Certain areas are covered by fine swampy sediments. Concepción is located in an area of varied lithology, but the greater part is over unconsolidated sands, and clays, of fluvial origin. Certain districts are constructed over other rocks of different sorts and of unconsolidated sediments: Lo Pequen, granite; Cerro Chepe and part of La Polvora, granite and sedimentary rocks; the blocks between Calles Martinez Rozas, Las Heras, Lincoyan, and Caupolican, Tertiary sedimentary rocks.

Contacts: The superficial unconsolidated deposits are over the oldest rocks in frank angular discordance.

Weathering: The superficial deposits are not weathered, and only in the highest places of the plain has a humic soil developed.

STRUCTURE

The region appears to be built by three great tectonic blocks whose plains of contact or fracture have a north south trend. It is suggested that the three blocks are—to the east, the elevated block of coastal Cordillera; in the center, the descending block of the plain between Concepción and Talcahuano; to the west, the elevated block of the peninsulas of Tetas and Las Tumbes. The fracture between the eastern block and the central part would pass by the edge of the city of Concepción and continue along the coast of Penco to the north. The direction approximately north south of Rio Bio Bio between Concepción and Chiguayante probably is related to this supposed fault. A second fracture would separate the central block and the western block. Observations indicate that it would pass between Cerro David Fuentes and the peninsula of Las Tumbes. The peninsula of Las Tumbes has the form of an elevated block. This fault would continue towards the south along the straight coast between Rio Bio Bio and Coronel.

The authors suggest the existence of other secondary fractures. One of these will pass to the east of the hills La Polvora and Amarillo in Concepción. The other fracture would pass to the east of the hill Chepe and Chacabuco. These hills suggest the existence of tectonic blocks, uplifted in asymmetrical form and limited by faults to the east. The rocks are of granite in the western border. The sedimentary Cretaceous-Tertiary rocks overlie the granite with a very regular plane of contact, which inclines from 14° to 32° west. The sedimentary rocks cover the upper part of the western slopes of almost all the hills near Concepción. In the granite in the sedimentary rocks of Cretaceous-Tertiary age are old faults of different strikes and dips, but in general of small offset. Movement on these faults during gthe recent earthquakes was not observed.

In the region of Gualpencillo, Saint-Amand and Dingman suggest that normal faults form a tectonic graben formerly occupied by the Rio Bio Bio.

Historical Geology

The oldest recognized rocks are mica schists and quartzites. These rocks suggest the deposits of ancient clastic sediments, fine clays, silts, and sands in a great marine sedimentary basin. The age of formation of these sediments might range from pre-Cambrian to Upper Paleozoic. Later these rocks were regionally metamorphized, probably before Triassic time. The intrusive rocks were emplaced in Jurassic or Cretaceous time.

It is presumed that following the emplacement of the granites there came a period of erosion. In some parts the sea advanced and littoral sediments were deposited. The sediments were constituted of sands, gravels, clays, and silts, that contained marine fossils. The line of the coast advanced and withdrew many times in the Eocene and Lower-Tertiary times. During the continental phase of the environment, plant remains were deposited in the beds of coal. In Tertiary times the region was fractured, as may be observed today, into many blocks. These blocks from the principal features of the geography. In Quaternary times the region probably was above sea level and the action of the rivers was dominant in the low parts of the relief. In these low areas sediments transported from eastern regions were deposited in the low places under the effects of glaciation. The assemblage of these unconsolidated sediments constructed a plain around "island mountains" of granites and Cretaceous-Tertiary rocks. Over these plains were erected the largest part of the works constructed by man.

Subterranean Water

The subterranean saturated zone is of great interest in regard to this report. The data in table 2 refer to the depth of the phreatic surface measured from the surface of the soil. Table 1 concerns the lithologic profile of some wells. The phreatic level at and near Concepción varies between 4.35 meters and 0.97 meter.

TABLE 2

Phreatic Level and Location of Wells

Number on the map	Location	Phreatic level, m
	Concepción	
1a	Calle Camilo Henriquez, N°1056	4.25
2a	Calle General Cruz, N°1957	4.35
3a	Calle Ainavillo, N°965	0.96
4a	Calle Carrera, N°1632	1.41
5a	Calle Janequeo, N°862	2.13
6a	Calle Las Heras, N°1145	2.45
7a	Calle Prieto, N°550	1.92
	Chiguayante	
—	Calle Lord Cochrane at the river	3.35
	Gualpencillo	
—	Price property	1.70
—	Four wells not shown on map	1.70–1.92
	Steel Plant	
—	Two wells not shown on map	0.0 and 2.0
	Salinas (Talcahuano)	
8a	No. 4118, Talcahuano Rd.	1.47
	Poblacion Gaete (Talcahuano)	
9a	Echeverria, N°441	1.46

Earthquake Phenomena

Characteristics of the Earthquake

Most of the damage in Concepción occurred following an earthquake at 0602 local time, on 21 May 1960. The epicenter seemed to be on the Arauco Peninsula, south of Concepción. The shock had a magnitude of $7\frac{3}{4}$ and produced Mercalli Intensities of IX in Concepción.

The large shock of the 22nd, at about 1510, although of magnitude $8\frac{1}{2}$, did little more damage in Concepción. Numerous aftershocks followed.

Expressions of the Earthquake in the Morphology

Landslides in the Modern Deposits of the Rio Bio Bio: According to verbal information from Professor Carlos Veyl of the University of Concepción, the earthquake of the 21st of May caused landslides in the eastern side of the bar in the mouth of Rio Bio Bio. The lengths of these slides are approximately 80 meters and the depth about a meter and half. When this place was visited 25 days after the earthquake, it was possible to verify the existence of these planes of sliding even though the depths and lengths were observed to be less than those stated. Apparently the rain waters modified these structures formed in the incoherent sands of the bar.

Slides in Steep Areas: In the eastern edge of Cerro Chepe are small semicircular landslides with a sliding area of about 50 m^2. The slide rocks are of the Tertiary-Cretaceous sedimentary complex and of decomposed granite. On the extreme west of Calle Lientur, in the eastern edge of Cerro La Polvora, a semicircular fracture with a throw of some 30 cm and a length of about 50 meters presents a great danger to the houses at the foot of the hill. In the same place, there occurred small slides as a result of the earthquakes. About 200 to 250 m^2 is in danger of sliding. The land in this place is composed of Cretaceous-Tertiary rocks and decomposed granite. The fractured block should be removed or stabilized.

At the southeast of the cemetery, on the western edge of Cerro Chepe, some 200 meters from the entrance to the road leading to the Bocotoma Corfo, there is a slide of approximately 50 m^2 composed of granite and plant debris. In this place there is danger of further landsliding.

At the extreme west of the bridge over the river Andalien, slides obstructed part of the road to Penco. The landslide occurred after the earthquakes of 21 and 22 May and was probably due to solifluction.

Mud Volcanoes: In the southern part of the mouth of the Rio Bio Bio, immediately next to the bar and some 100 meters from the river, there were numerous mud volcanoes associated with east-west fractures about 50 meters long having a vertical throw of 5 cm. Mud volcanoes are observed in the lower of two terraces that have a 2-meter difference in altitude between them. The diameter of some of the "sandblows" reached 80 cm with altitudes of up to 30 cm.

Compaction of the Soil and Artificial Fill: Because of soil compaction, many buildings in Concepción and its suburbs settled unevenly. The chemistry building at the University has a 20-cm difference in level between two of its sections. Similar phenomena were observed in the sugar refinery at Penco. In Lorenzo several houses have sunk about 15 cm below the level of the sidewalk. The approach to the overpass on the road to Talcahuano sunk about 39 cm.

The bridge over Rio Bio Bio was seriously damaged by settling of artificial fill. The extreme north end sank about 40 cm. The pillars supporting the bridge here fell and the northern sections collapsed. The pillars were inclined to angles of 75 and 80 degrees up to 200 meters from the north bank.[1]

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[1] Translator's note: Upon examination of this bridge by Dr. Erickson and myself, it was observed that by sighting along the railing of the bridge one could see that the southern part of the bridge had been deflected about a foot and a half to the west with respect to the northern part. The damage to this bridge in our opinion was due as much to actual fault movement as to settlement of foundation material.

Effects of Earthquakes in the Structures Made by Man

Buildings: Four traverses of the city of Concepción were made in order to study the damage produced by the earthquakes. The type of damage and the type of material used in the construction was noted. The authors chose two streets with a northeast-southwest direction and two in a southeast-northwest sense to cover a wider region and range of soil qualities. The traverses were made along one side of

TABLE 3

CENSUS OF THE DAMAGE IN CONCEPCIÓN ALONG THE TRAVERSE: LORENZO ARENAS—LAS HERAS LIENTUR MARTINEZ DE ROZAS—HIPOLITO SALAS—LAS HERAS SANHUEZA

Type of construction	No. of buildings	Buildings damaged	%	Cracked buildings	%	Buildings with fallen walls	%	Buildings with fallen roofs	%	Wooden buildings twisted	%	Buildings completely destroyed	%
Adobe	4	4	100	1	25		—	—	—	—	—	3	75
Combination of adobe and brick united with mud	16	16	100	1	6.25	1	6.25	3	18.75	—	—	11	68.75
Combination of adobe and wood	1	1	100	1	100		—	—	—		—	—	—
Brick united with mud	19	19	100	8	42.10	3	15.79	1	5.26	—	—	6	31.58
Combination of bricks united with mud and bricks united with mortar	1	1	100	1	100	—	—	—	—	—	—	—	—
Bricks united with a mixture of mortar and sand	99	39	39.39	27	27.27	5	5.05	2	2.02	—	—	—	—
Combination of bricks and wood	1	1	100	—	—	1	100	—	—	—	—	—	—
Reinforced concrete pillars and beams with brick filler walls	1		—	—	—	—	—	—		—	—	—	—
Reinforced concrete	3	—	—	—	—	—	—	—	—	—	—	—	—
Wood	57	1	1.75	—	—	—	—	—	—	1	1.75	—	—
Total	202	82	40.1	—	—	—	—	—	—	—	—	—	—

TABLE 4

CENSUS OF DAMAGE ALONG THE TRAVERSE: LIENTUR—RODRIQUEZ—NONGEN

Type of construction	No. of buildings	Buildings damaged	%	Cracked buildings	%	Buildings with fallen walls	%	Buildings with fallen roofs	%	Wooden buildings twisted	%	Buildings completely destroyed	%
Combination of adobe and brick united with mud	3	3	100	1	33.33	—	—	1	33.33	—	—	1	33.33
Bricks united with mud	9	9	100	3	33.33	3	33.33	—	—	—	—	3	33.33
Bricks united with mortar	22	11	50	5	22.72	2	9.09	1	4.54		—	3	13.63
Combination of bricks and wood	2	—	—	—	—	—	—	—	—	—	—	—	—
Reinforced concrete pillars and frames with brick filler walls	15	7	46.66	7	46.66	—		—	—		—	—	
Unreinforced concrete	3	—	—			—	—		—	—	—		
Combination concrete and wood	4	—	—	—	—	—	—	—	—	—	—	—	—
Wood	23	1	4.34	—		—	—	—	—	1	4.34	—	—
Total	81	31	38.27		—	—	—		—	—	—	—	—

TABLE 5

Census of Damage Along the Traverse: Pedro de Valdivia—Esmeralda—Serrano—Prieto—Arturo Prat—Magallanes—Marina de Chile

Type of construction	No. of buildings	Damaged buildings	%	Cracked buildings	%	Buildings with fallen walls	%	Buildings with fallen roofs	%	Wooden buildings twisted	%	Buildings completely destroyed	%
Adobe	9	9	100	1	11.11	—	—	—	—	—	—	8	88.88
Combination adobe and brick united with mud	6	6	100	4	66.66	1	16.66	—	—	—	—	1	16.66
Brick united with mud	18	18	100	4	22.22	9	50	2	11.11	—	—	3	16.11
Brick united with mortar	89	71	79.76	42	47.19	17	19.1	6	6.74	—	—	3	3.37
Combination of bricks and wood	3	2	66.66	1	33.33	1	33.33	—	—	—	—	—	—
Reinforced concrete frame with brick filler walls	3	1	33.33	1	33.33	—	—	—	—	—	—	—	—
Unreinforced concrete	1	1	100	1	100	—	—	—	—	—	—	—	—
Reinforced concrete	12	2	16.66	2	16.66	—	—	—	—	—	—	—	—
Wood	36	3	8.33	—	—	—	—	—	—	3	8.33	—	—
Total	177	113	63.84	—	—	—	—	—	—	—	—	—	—

TABLE 6

Census of Damage Along the Traverse: Chacabuco—Andres Bello

Type of construction	No. of buildings	Damaged buildings	%	Cracked buildings	%	Buildings with fallen walls	%	Buildings with fallen roofs	%	Wooden buildings twisted	%	Buildings completely destroyed	%
Adobe	3	3	100	2	66.66	1	33.33	—	—	—	—	—	—
Combination adobe and brick with mortar	1	1	100	1	100	—	—	—	—	—	—	—	—
Combination adobe and wood	6	6	100	3	50	2	33.33	—	—	—	—	1	16.66
Brick united with mud	17	15	88.23	—	—	3	17.64	3	17.64	—	—	8	47.05
Combination brick united with mud and brick united with mortar	7	7	100	1	14.28	—	—	—	—	—	—	6	85.71
Brick united with mortar	17	15	88.23	9	52.94	2	11.76	1	5.88	—	—	2	11.76
Combination of bricks and wood	2	2	100	2	100	—	—	—	—	—	—	—	—
Reinforced concrete frame with brick filler walls	5	—	—	—	—	—	—	—	—	—	—	—	—
Unreinforced concrete	1	1	100	1	100	—	—	—	—	—	—	—	—
Reinforced concrete	11	3	27.27	3	27.27	—	—	—	—	—	—	—	—
Wood	14	2	14.28	—	—	—	—	—	—	2	14.28	—	—
Total	84	55	65.4	—	—	—	—	—	—	—	—	—	—

each street. The traverses were as shown in tables 3 to 6 which indicate in a very general way the type of damage observed and the materials used in the buildings. The classification of the damage and of the types of construction was generalized to make understanding simpler. For the types of damage, the authors used a scale of six steps of destruction, from minor damage to complete destruction of the building. The types of materials used in the construction have been divided into 13 classes, not all of which were found in each traverse. Some types of construction

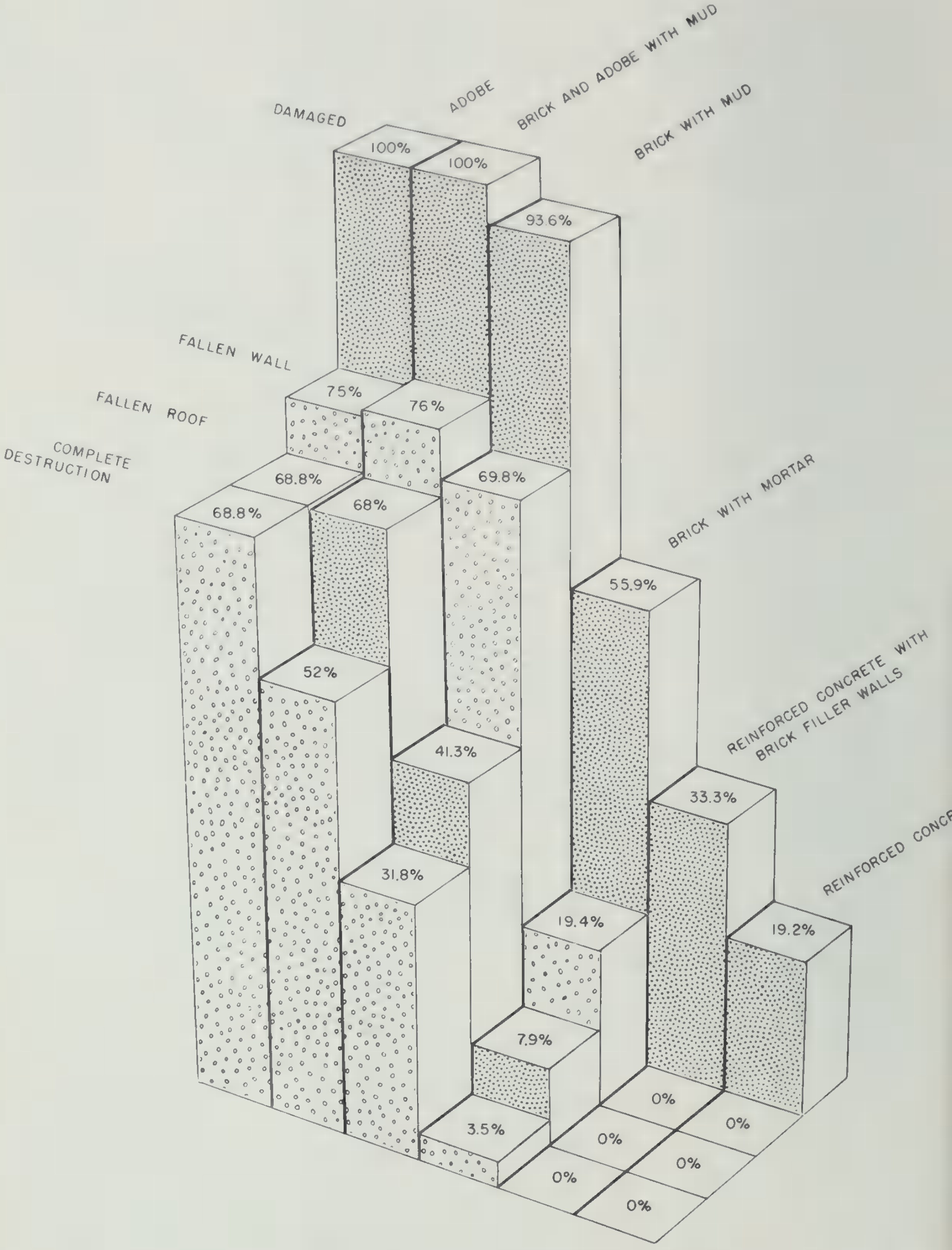

Fig. 2. Percentages and Types of Damage in the Construction Materials of Buildings.

are scarcer than others, so the percentage of the type of damage was reported only in construction materials used in more than ten houses (figure 2).

The data of tables 3, 4, 5, and 6 are presented again in table 7, in digested form, and are also displayed in figure 2, which shows the percentage of houses of a given type damaged, the type of damage, and the types of construction. Wooden buildings are not included.

Because different classes of land coincide with great differences in construction of materials used, the relation between the condition of the land and damage suffered by the houses built on it is not a simple one.

TABLE 7

CENSUS OF DAMAGE IN THE CITY OF CONCEPCIÓN

Type of construction	No. of buildings	Damaged buildings	%	Cracked buildings	%	Buildings with fallen walls	%	Buildings with fallen roofs	%	Wooden buildings twisted	%	Buildings completely destroyed	%
Adobe	16	16	100	4	25	1	6.25	—	—	—	—	11	68.75
Combination of adobe and brick with mortar	1	1	100	1	100	—	—	—	—	—	—	—	—
Combination of adobe and brick with mud	25	25	100	6	24	2	8	4	16	—	—	13	52
Combination of adobe and wood	7	7	100	4	57.15	2	28.57	—	—	—	—	1	14.28
Brick with mud	63	61	96.83	15	23.81	18	28.57	6	9.52	—	—	20	31.75
Combination brick with mud and with mortar	8	8	100	2	25	—	—	—	—	—	—	6	75
Brick with mortar	227	136	59.91	83	36.56	26	11.45	10	4.41	—	—	8	3.52
Combination of bricks and wood	8	5	62.5	3	37.5	2	25	—	—	—	—	—	—
Reinforced concrete with brick filler walls	24	8	33.33	8	33.33	—	—	—	—	—	—	—	—
Unreinforced concrete	5	2	40	2	40	—	—	—	—	—	—	—	—
Reinforced concrete	26	5	19.23	5	19.23	—	—	—	—	—	—	—	—
Combination, reinforced concrete	4	—	—	—	—	—	—	—	—	—	—	—	—
Wood	130	7	5.38	—	—	—	—	—	—	7	5.38	—	—
Total	544	281	51.6	—	—	—	—	—	—	—	—	—	—

Damage to the Steel Company of the Pacific: On the 29th of June 1960 the authors, Sr. Ernest Dobrovolny, Richard Lempke, and Robert Devaul were guided by Sr. Fred K. Coleman through the parts of the steel plant that were most affected by the earthquake of the 21st of May. The plant has operated since 1949. Present production is 375,000 tons per year. The altitude above sea level is 5 meters. The water table varies between 2 and 3.6 meters below the land surface. When the earthquake occurred, the pipeline broke in two places and the plant remained without water, electricity, or steam. Production did not suffer, because repairs were made in time. The blast furnaces were anchored to blocks of concrete about 10 feet by 10 feet and buried between 8 and 10 feet deep. The movements of the earthquakes stretched the bolts about 2 inches. In the coking plant, designed to resist earthquakes, diagonal shear fractures were noted.

Damages in the Sugar Refinery at Penco: The refinery was visited the 2nd of July 1960 to study the damage produced by the earthquake of the 21st of May. The authors were kindly accompanied by an engineer of the company. One of the buildings is constructed of brick and cement, with beams of steel. The earthquake cast down the north wall, and the south wall will have to be demolished. The purification retorts rotated several inches in one of the neighboring buildings. Another of the buildings, apparently because of its great weight, sunk into the soil. The horizontal steel beam of this building was bent in compression. One building, 70 years old, had a fracture that was caused by the earthquake in 1953 and was reactivated in that of the 21st of May 1960. The building is of brick, with concrete pillars. The northern wall sank some 2 cm owing to heavy equipment on the second floor. The second floor is sustained by horizontal steel beams that in their turn are supported by the north wall.

On the western side of the sugar refinery, across the street that separates it from the stadium, is a fault with a strike N17°W that dips to the northeast some 30 degrees, on which the northeastern block has sunk some 2 cm. The fault affects the pavement of the street, the sidewalks, and the walls of the building.

Conclusions

Earthquake damage to buildings depends clearly on the material and type of construction. The authors could not establish a relation between the damage of buildings and the types of rock upon which the city of Concepción is constructed. The authors observed that those buildings constructed following studies of the mechanics of the soil over which they are seated, resisted the earthquakes very well. Buildings of wood and of reinforced concrete best resisted the earthquake movements, regardless of the rocks or sediments on which they were seated.

New construction of adobe or brick should not be authorized if the bricks are united with mortar poor in cement, or with mud. The buildings constructed with this class of materials have suffered the greatest damage by seismic waves, independently of the condition of the ground.

In Concepción there is no evidence that houses constructed over zones of artificial fill have suffered more than other houses constructed with similar materials over natural soils; however, the north end of the railway bridge over Rio Bio Bio, placed on artificial fill, suffered great damage. Similar observations were made concerning the overpasses. Evidence collected in the study of the damage caused by the earthquakes in other places of the world indicates that artificial fill is probably the poorest foundation material.

Acknowledgments

Ernest Dobrovolny and Richard Lempke, geologic engineers of the Geologic Survey of the United States, made valuable criticisms and suggestions for the preparation of this report.

The Department of Geology of the University of Concepción, through the efforts of Senor Carlos Veyl, collaborated in numerous material ways and gave valuable information on effects of the earthquake and on the geology.

We also acknowledge the information concerning wells and soundings given by the Steel Company of the Pacific, the Office of Public Works, and the National Service of Health.

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RELATION BETWEEN GEOLOGY AND THE DAMAGE IN PUERTO MONTT, CHILE, CAUSED BY THE EARTHQUAKE OF 22 MAY 1960

By Ernest Dobrovolny, Richard Lemke, William Bowes, Herbert Thomas, and Nelson Bravo S.

(Translated and Abridged by Pierre Saint-Amand)

ABSTRACT

The damage in Puerto Montt resulted from landsliding, debris flows, mud flows, and settling of unconsolidated alluvium and artificial fill. Structures on high terraces, away from the edges, were undamaged.

Introduction

The city of Puerto Montt, in southern Chile, is located on the north coast of the Bay of Reloncavi, some 75 km, in a straight line, east of the ocean and 21 km south of Lago Llanquihue (figure 1 in the pocket at the back of this issue).

The purpose of this preliminary report is to present geologic information adequate for reconstruction in Puerto Montt, which was ravaged by the earthquake of 22 May 1960. Information is presented concerning the different types of geologic materials that underlie the city and the relation between them and the damage produced by the earthquake.

Ernest Dobrovolny, Richard Lemke, and Herbert Thomas spent the 11th to the 18th of July 1960 preparing a geologic map (figure 2 in the pocket at the back of this issue) and studying the area. Thomas, Bowes, and Bravo were in the area between 22 June and 12 July recording information and studying the location and extent of landslides and slumps produced by the earthquake.

Because of the short time available and the lack of subsurface data, the location of the contacts that separate the geologic units is more refined in those places where more geologic data and better base maps were available. The map should not be too rigorously interpreted with respect to the contacts between the various types of geologic material.

A map of the city with 10-meter contour lines, made available by the city architect, Sr. Elizardo Bravo S., was used. A part of the geologic mapping was done with the aid of air photos.

Puerto Montt has about 3,300 inhabitants. A great part of the residential area of the city is situated over two conspicuous terrace levels that border the north coast of the bay of Puerto Montt. The largest part of the commercial district and part of the residential district lie upon lower alluvial deposits and over artificial fill along the coast of the bay.

The level of the higher terrace forms a relatively flat plane about 107 meters above mean sea level. The surface of the lower terrace, some 45 meters above mean sea level, consists of a series of terrace remnants. Some remnants of the other terraces exist both above and below the 45-meter terrace. Alluvial deposits of debris and of mud flow material constitute surfaces varying in declivity from very steep to almost flat, inclined towards the bay. A narrow terminal moraine, several meters in altitude, forms an arc that limits the city on the north and northeast.

Geology

Regional Setting: No lithified rocks have been encountered in the immediate vicinity of Puerto Montt. The hardest rocks known nearby are along the east coast of the Bay of Reloncavi and along the east coast of Lago Llanquihue. According to Brüggen (1950) these outcrops are of Cretaceous diorite for the most part. In this area are two volcanoes surrounded by very recent volcanic rocks.

The area north and east of Puerto Montt and the islands at the extreme southwest of the Bay of Reloncavi consist of glacial deposits of Pleistocene age. Well-stratified deposits of fluvioglacial materials more than 30 meters thick form steep escarpments and well-defined terraces along the coastline west of the Bay of Reloncavi. The high lands north and northwest of Puerto Montt are modified by interconnecting wide and level fluvial canals filled with fluvioglacial materials. A terminal moraine is seen to the north and northwest of the city, and it is probable that the islands situated to the southeast of the Bay of Reloncavi are also formed of terminal moraine deposits.

Puerto Montt is constructed on Pleistocene and Recent deposits. The deposits have been subdivided into the 10 units described below:

Lacustrian Deposits: In the port area to the southwest of the city, about 19 meters of finely laminated beds of silt and clay are exposed. The beds resemble varves. A measured section in this locality is described as follows:

Meters Above Sea Level	Description
0–4.56	Covered, probably mostly artificial.
4.56–23.46	Silty clay and clayey silt, finely laminated. Dark gray lamina 1 mm thick, light gray lamina up to 7 mm thick. Some beds lightly to moderately contorted. Near the upper part, the deposits are more clayey and more finely laminated and varve-like, colored lightly with limonite along the beds.
23.46–23.96	Sand, dark gray, medium to fine; well stratified. The upper contact is marked by a line of residual, concentrated boulders.
23.96–25.96	Colluvium and torrential materials, reddish, coffee-colored clayey silts.
25.96–31.06	Cover. The upper part forms a flat terrace surface.

In a road cut along the coast, immediately to the southeast of Puerto Montt and in the neighborhood of the arroyo Pelluco E., there are more than 5 meters of glacial deposits exposed. The glacial materials are covered in part discordantly by morainic material. Fossil wood is found in the lacustrian deposits at about 2 meters above the level of the road. Specimens of the wood were taken to determine the age of the deposits by means of carbon 14.

Fluvioglacial Sediments of the Wide Terraces. The fluvioglacial material underlies two distinct levels of the broad terraces of the city. The north and northwest edges of the city are constructed over the higher of the two levels, an almost level surface 107 meters above sea level, where the principal residential buildings are situated. The few large structures include the Regional Hospital, a building of the Catholic Seminary, and a large building, under construction, of the Catholic College. Some remnants of terraces with flat surfaces are found at levels a little above and below that of the 45-meter terrace and that of the 107-meter terrace. In this geologic unit is included fluvioglacial material deposited in a wide fluvioglacial canal with a flat bottom level with the 107-meter terrace. The fluvioglacial material extends locally to an altitude of 115 meters; in some places it underlies materials of a terminal moraine. The outcrops are limited in large part to some road cuts, landslide scarps along the edges of terraces, and excavations for gravel located in fluvioglacial canals. The maximum thickness of the deposits is not known, but it is thought that in all parts it is at least as thick as the altitude of the terrace.

The deposits consist of well to poorly classified beds of gravel and generally well-stratified beds of a clean coarse sand. Some beds are well defined; others are gradational with the strata both above and below. The material, of pebble size, consists predominantly of granitic and volcanic rocks.

A typical section, which begins 19 meters above sea level, in a road (Calle ejercito) cut near the Catholic Seminary and extending to the northwest up to the upper surface of the terrace at 107 meters, is described as follows:

Meters Over Sea Level	Description
19.0–48.4	Gravel, medium to coarse (max. size about 15 cm, average 7 cm). Poorly classified and ill-defined stratification. The beds are inclined 20 degrees to the northwest, suggesting that the material has been deposited by ice in the bay to the southeast. Near the top are some beds of coarse sand. Material the size of pebbles of granitic and volcanic rocks forms the upper part of the lower terrace.
48.4–68.8	Covered.
68.8–77.6	Sand, gray, fine to medium grain, finely stratified, clean, well classified except for some isolated pebbles between 5 and 7 cm in length. Well compacted. Near the top are strata and veins of fine yellowish silt (about 2 cm).
77.6–86.3	Gravel, fine to medium (up to 20 cm in diameter), poorly classified with clayey matrix. A yellow film of clay covers many of the stones. Similar to material on the lower terrace.
86.3–92.1	Sand, dark gray, medium to coarse, well stratified, moderately compacted. Some veins of gravel encountered near the upper part. Inclination of beds irregular, but average 10 degrees to the south.
92.1–101.6	Gravel, similar to the strata 77.6–86.3. Some granitic pebbles with much decomposed biotite. The pebbles are angular to well rounded.
101.6–106.8	Gravel, medium to coarse, almost without classification. Abundant patina of yellowish to orange limonite. Lower contact is irregular cut and fill channels of 1-meter depth noted in the lower beds.
106.8–107.3	Weathered zone. Clay, silty, reddish coffee color, covered by 25 cm of black soil (horizon A). Upper part of second terrace. The section continues some 700 meters to the west in an excavation of gravel near the road to Chin-Chin; the section will be described in the discussion of the terminal moraine material.

Another section of fluvioglacial sediments that forms the level of the largest lower terrace was measured along the scarp of a giant landslide in the southwestern part of the city, some 300 meters northeast of the outcrop of the lacustrian deposits. In this section, beds of sand and gravel similar to those previously described are not observed. Lacustrian deposits do not exist below the sand and gravel of this outcrop, but lacustrian deposits at a lower altitude suggest that the gravels and sands may also be resting on lacustrian deposits.

Fluvioglacial Sediments of Cut Terraces. These deposits are confined to the western part of the city. Discontinuous outcrops may be observed in dissected terraces that can be correlated in large part with the 45-meter terrace. The local relief is large and many slopes are steep, especially in the northwestern part of the unit.

The thickness of the deposits is not known, but is probably as great as or greater than the heights of the terraces. The deposits are similar to those of the fluvioglacial sediments that form the high terraces.

Nonetheless, in the majority of the outcrops the beds of sand are thicker than those of gravel. The sand is in the largest part dark-gray, clean, well-stratified, and moderately compact. The majority of the beds are essentially horizontal. The sand is easily eroded and this probably explains the high state of dissection in the remains of the terraces. As a result, in many places there is much finer cover of weathered material than there is on the wide terraces. Nevertheless, in some places a bed of coffee-colored silty clay with a thin bed of black soil (horizon A) about a half meter thick covers the unweathered deposits.

Terminal Moraine Deposits. A terminal moraine, poorly to well defined, delineates the northern and northeastern part of the city. In most places, the moraine is less than 10 meters high and forms a small ridge upon which cobbles and boulders crop out. Exposures are limited to two gravel pits and some road cuts.

The deposits are in part moraines with stratified intercalations. In many places, less than 10 meters of thickness may be observed and the moraine deposits overlie the fluvioglacial sediments that form the terrace deposits. The contact between the morainic material and the fluvioglacial sediments is irregular and probably was a pre-existing surface of fluvioglacial materials over which was deposited another mantle of fluvioglacial sediments.

Meters above sea level	Description
111.8–115.8	Sand and fine gravel, well classified, clean; some cross-bedding. Upper contact irregular.
115.8–118.8	Silt and sand, almost varved, fine laminations, strata contorted around the stones. A few boulders of about 7 inches diameter and some boulders of up to 70 cm diameter. Near the upper surface some irregular inclusions of morainic material up to 1 meter in diameter.
118.8–119.4	Weathered zone, yellow silty clay.
119.4–119.5	Weathered zone, reddish silty clay (soil horizon B).
119.5–119.6	Weathered zone, black humic material (soil horizon A).
119.6–123.5	Gently sloping cover. Underlies morainic material; boulders on the surface.

The morainic materials consist mostly of unstratified sand, gravel, cobbles, and boulders. In some places, the morainic material is weathered to a 65-cm depth.

Two sections were measured that show the nature of the terminal moraine deposits and their relationship to the underlying fluvioglacial deposits.

A measured section of gravel pits along a circumvallated road, near Chin-Chin, is described above.

A second measured section in a gravel pit several blocks northwest of the city is as follows:

Thickness In Meters	Description
4.2	Clean, gray, coarse sand, well stratified, some cross-bedding, lenticular sand and gravel.
2.0	Beds of gravel up to 1 meter thick; contains some semirounded boulders of morainic material (grayish coffee color, with cobbles up to 5 cm in diameter).
1.5	Morainic material, grayish coffee-colored sand with abundant cobbles and some boulders up to 0.3 meter in diameter. Well compacted.

Deposits of Colluvium and Slide Material on Strong Slopes. The material accumulated over steep slopes by mass movement, by torrential washing of slopes, and by slide materials is described in this unit. The colluvium is defined as a combination of mass movement debris and slope wash materials. The slide material is a combination of debris flows and slump block.

This unit is distributed in most part along the steep sides of the terrace at 45 and 107 meters. The outcrops are some small scarps in slide material and some road cuts.

The colluvium, which includes a soil profile, is generally 1 to 2 meters thick and consists principally of reddish, weathered, silty clay. In some places it is slightly stratified parallel to the slope. The colluvium is over fluvioglacial sediments that form the terraces; the contact between the two is gradual.

The slide materials included in this unit are observed in many places along the bold scarps of the terrace. At least three of the slides are very recent, even antedating the earthquake, as may be seen by fresh scarps and piles of material not covered by vegetation at the foot of steep slopes. Many older slides now covered by brush and small trees may be seen. Their presence may be inferred from the topography of ridges and hollows that characterize the indistinct scarps.

The slide material consists of colluvium and the underlying sands and gravels that form the fluvioglacial sediments of the terraces. The thickness of the deposits varies from less than 1 meter to about 5 meters.

Mud Flows, Debris Flows, Landslides, and Older Alluviums. This unit is in general poorly defined geographically and geologically. It includes parts of the central and northern sectors of the city, occupied principally by residences and partly by the commercial district in the center of the city. The major part of the area covered by this unit is stratigraphically below the terrace deposits, and represents in large part material derived from these terraces by down-slope movement of debris, earth slides, and rain wash of slopes, both in historic and prehistoric time. It is probable that the unit consists in large part of poorly consolidated silts, sand, gravel, and humic material. The outcrops are nevertheless insufficient to determine the exact composition of the deposits.

The deposits of mud flow, debris flows, and landslides are principally confined to the northern part of the city, such as the northern part of Barros Arana and the western part of San Ignacio, where the slopes are steeper. Nevertheless, the original configuration has been extensively modified by slope wash and erosion, so that they are now badly defined. The erosion of the material resulted in their redeposition as alluvium in the central part of the city. Nevertheless, the area to the west of the main road to Puerto Varas has suffered little erosion since its deposition, and maintains much of its original topography. This inclined surface is composed of humps and hollows, with numerous closed depressions occupied by small swamps. The surface is covered by grass and gray to black soil about 1 meter thick. There is no evidence of recent landslide scarps or cracks.

Some new shacks are being constructed in this area, probably by people who lost their homes in the earthquake.

The thickness of the deposits in this unit is unknown, but probably does not exceed many meters. These deposits may in many places overlie stratified fluvioglacial sediments of similar composition to those underlying the terraces. In some places they cover swamp and marsh deposits. A small lake, now filled, formerly existed in part of the commercial district.

Debris Flow of 1957. A debris flow of recent aspect occurred in 1957 and occupies an area of irregular shape on both sides of the highway that leads to Puerto Varas. It occurred during a rainy spell while a deep cut was being prepared for the construction of the highway. The irregular surface of the flow is now covered by bushes.

The flow moved rapidly downslope and must have been in part a mud flow. This is suggested by the fact that the flow is less than 2 meters thick and moved over across very moderate slopes.

The material displaced by the flow consists of sand and gravel mixed with colluvial material. To the east of the road it is in great part over fluvioglacial terrace material; to the west of the road it is over deposits of older earth slides.

Deposits of Mud Flows, debris flows and Landslides (Resulting From the Earthquake of 22 May 1960). The earthquake of 22 May 1960 triggered mud flows, debris flows, and landslides in three parts of the city. The landslide occurred in the steep slopes and as a consequence made steep scarps on the upper part. The debris accumulated at the foot of the slopes.

The steep slope to the north of the docks, Puerto 470-B, in the southeastern part of the city is composed of landslide materials. This area has a total relief of 75 meters, with a head scarp of some 5 meters and fractures parallel to the slope uphill of the scarp. The material has moved down principally as a type of fluid debris flow and has formed a definite salient down the steepest slope of the colina. In the lower part, the flow reached a thickness of several meters. The greater part of the material consisted of medium-to-coarse sand derived from the fluvioglacial material of the terrace that underlay the slide. About 2 meters of finely laminated, plastic silty clay that crops out near the head of the slide area was swept up in the slide. Colluvium and slope wash material about 1 meter thick were also incorporated in the slide. There were no springs in the slide area when it was mapped, even though the deposits were completely saturated.

A second area with slide material, which caused the greatest loss of life and property in Puerto Montt, took place on a strong slope to the west of Calle San Ignacio in the north central part of the city. A later prominent scarp marks the upper limits of the slide area as such; nevertheless, numerous fresh fractures to the west, which extend behind the face of the scarp for some 75 meters, show that the material is highly unstable and can slide at any moment, even without an earthquake. The material of the slide moved rapidly downhill as a mud flow and extended across the relatively flat soil for a distance of two blocks, across Calles San Ignacio and Christian Brahm. The houses in the path of the material were destroyed, with a consequent loss of lives. The slide material was deposited with a thickness of several meters near the extremities of the slide area. The material that constituted the slide deposits is mainly sand, with lesser quantities of gravel derived from the fluvioglacial deposits of the terrace. A small amount of colluvial material originally on the slope was also mixed into the slide. A large flow of water came from the deposits of the slide area, increasing the fluidity of the deposits markedly and hence their susceptibility to move across relatively flat terranes.

The third slide occurred on the extreme west of Calle Malaquias Concha on a steep slope. This slide is similar in many respects to the second slide, described above, and involved similar materials. It was considerably smaller in extent and caused less damage, because the material moved down the street.

Beach Deposits. These are mostly sand. Only that part of the beach between high and low tides is exposed. Other beach deposits underlie artificial-fill material behind the sea wall and material in the dock area to undetermined depths. The thickness of these deposits is unknown.

Artificial Fill. Gravel, sand, brick, wood, and mud constitute the ensemble of artificial fill that marks the coastline of the city. The outcrops were limited at the time of making the geologic map to some few man-made trenches, hence the exact composition and thickness in any locality is unknown. The height of the sea wall gives some idea of the maximum thickness of the fill. The thickness is probably 3 or 4 meters at the docks and near the sea wall, from which line the thickness gradually decreases to zero as one goes inland. The areal limits of the fill, as shown on the map, are imperfectly known and the contacts with the other deposits can only be refined where data from the subsurface are obtained. Furthermore, other areas of the city may be underlain by artificial fill of unknown extent and thickness. These probable areas are not shown on the map.

Geologic Structure

The lakes of southern Chile occupy a long fossa, limited by one or more faults that have an approximately north-south direction (Brüggen 1950; Muñoz-Christ, 1956). The Bay of Reloncavi and others to the south of Puerto Montt were originally lakes that have been submerged below sea level. As Puerto Montt is about on the midpoint of the line of lakes, some faults may exist to the east and west of the city.

No evidence of active faulting was observed in the vicinity of Puerto Montt. It is suggested, nevertheless, that a small fault may exist in the southeastern side of the city in a deep straight valley. The displacement is along an almost vertical line. It has a southeasterly strike and is covered by about 1 meter of undistorted alluvium. This displacement may be the surface expression of a deeper movement.

In the section on geologic manifestations of the earthquake, fractures in pavement and in landslide scarps, resulting from differential compaction and superficial movement, were discussed. These are expressions only of superficial movement and are clearly not tectonic.

Characteristics of the Earthquake of 22 May 1960: According to Pierre Saint-Amand (oral communication), the intensity of the main earthquake varied between Mercalli VII and XI. The lesser intensity of VII was assigned to the areas on the 45 -and 107-meter terraces. The XI was assigned to a filled area near Avenida Costanera Diego Portales.

The inhabitants of Puerto Montt reported the movement to be a smooth swaying. There was no unanimity of opinion as to the direction of movement. This lack of accord suggests that the movement was oscillatory.

There was no maremoto at Puerto Montt. The nearest tsunami occurred at Ancud, some 85 km west. Several people reported a slight rise in water level in the bay at the time of the earthquake.

Geological Expressions of the Earthquake: The effects in the soil of the earthquakes were expressed by superficial fractures, displacement along fractures, landslides, debris flows, and slumps along the sides of incised valleys. Distortion of the surface is more concentrated in young alluvial deposits than in other materials.

The waterfront has been artificially filled. In places the surface shows only open fractures and in others displacements of up to 1 meter in height along the fractures. In areas such as this, where the fill is presumably thick, many buildings still standing are tipped at odd angles and others are completely destroyed.

The greatest destruction occurred in the extensive dock 470-B; here the sea wall fell and the artificial fill ran into the bay. The fractures and the scarps along the fractures are the result of differential compaction and of the displacement of material by flowage into the Bay of Reloncavi.

The mud-flow deposits, debris flows, and slide material are combined in one map unit because of similarity of form and mechanics of movement. Examples of this type of nontectonic behavior, provoked by the earthquake of 22 May 1960, are illustrated in three localities. The biggest is in the southwestern part of the city; here the upper part of the displaced material is marked by two clear scarps. The higher cuts the upper part of the 45-meter terrace; in its lower part, the material, mostly fine to medium sand, resembles a mud flow. The debris flow between Calles Santa Maria and Blanco Encalada, which crosses Christian Brahm, is several meters thick near its end; in the extreme upper part of the debris tongue there is an almost vertical scarp. On the smooth slope to the west of the scarp are open fractures along which there has been no noticeable displacement, but which presumably represent lines of weakness where future scarps may form. The debris flow destroyed all the houses in its path. The smallest of the debris flows extends from a sharp scarp on the east along Calle Malaquias Concha.

On the slopes covered with colluvium, between the two terrace levels, there are open fractures and slippage planes with about 2 meters of movement. If the soil had been saturated, as is the case in the rainy season, these displacements could have become destructive landslides or mud flows.

Damage to Man-Made Structures: Damage ranged from complete destruction to a few minor cracks in some of the better built structures. Some examples of damage can be seen in figure 3–11. While the authors' work was being done, university students under the supervision of architect Elizardo Bravo S. were collecting detailed information on the type and material of construction and the degree of damage. This material could be correlated with the soil conditions.

Relation Between Geology and Damage

From the observations made during the preparation of the geologic map, a general relation between the damage and the soil conditions stands out clearly. With certain exceptions, we will discuss this relation in order of age, going from the oldest deposits to the youngest. Let it be remembered that each relation is a generalization based on a hurried reconnaissance. The relations should be verified by an analysis of the data on damaged buildings collected by architect Bravo, when this information is available for study.

Lacustrian Deposits. Only a few ruinous wooden structures were built over lacustrian deposits. They were, as nearly as one could tell, undamaged.

Fluvioglacial Deposits of the Wide Terraces and Terminal Moraines. For purposes of discussion these materials are included as a unit, because there was little difference in the damage produced over them. Only slight damage occurred to the majority of structures on these materials. The notable exceptions to this observation are major structures such as the Seminary, located at the edge of the terrace in block No. 817, and the Regional Hospital next door; these are buildings of several stories that appear to be constructed of inferior material and not well reinforced. The Catholic College, in construction, located to the northeast of the Regional Hospital, was not seriously damaged. There was less damage on the 107-meter terrace than on the 45-meter terrace.

These terrace levels resist earthquake vibration better than any other terranes near Puerto Montt. Future construction should take place away from the edge of the terrace to prevent structures from sliding downhill during landslides.

Fluvioglacial Deposits. No significant damage was noted in the areas of fluvioglacial deposits on divided terraces. In the terraces the majority of structures are one-story wooden buildings that appear to have resisted the earthquake quite well. The areas of narrow valleys, escarpments, and moderate-to-sharp ridges are being actively eroded. In many places, weak sandy material can yield during any wet spell, as is evident from the quantity of material transported into the Bay of Reloncavi by the short steep arroyos during heavy rains. Although the area is now occupied by many one-story buildings, it is not advisable to erect urban or industrial districts in the future because of the high cost of construction methods necessary to control the erosion and because of the possibility of future landslides on steep slopes.

Deposits of Colluvium and Landslides on Steep Slopes. Many buildings located on these materials on steep slopes were extensively damaged and destroyed. The damage was done in two ways: (1) failure of material by downslope movement that

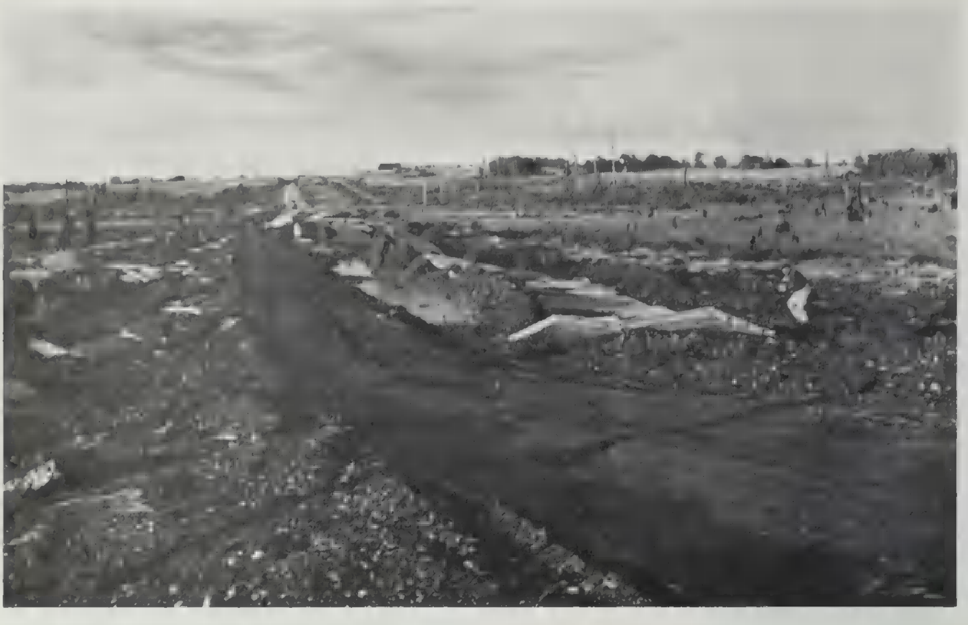

FIG. 3. Highway Between Puerto Varas and Puerto Montt.

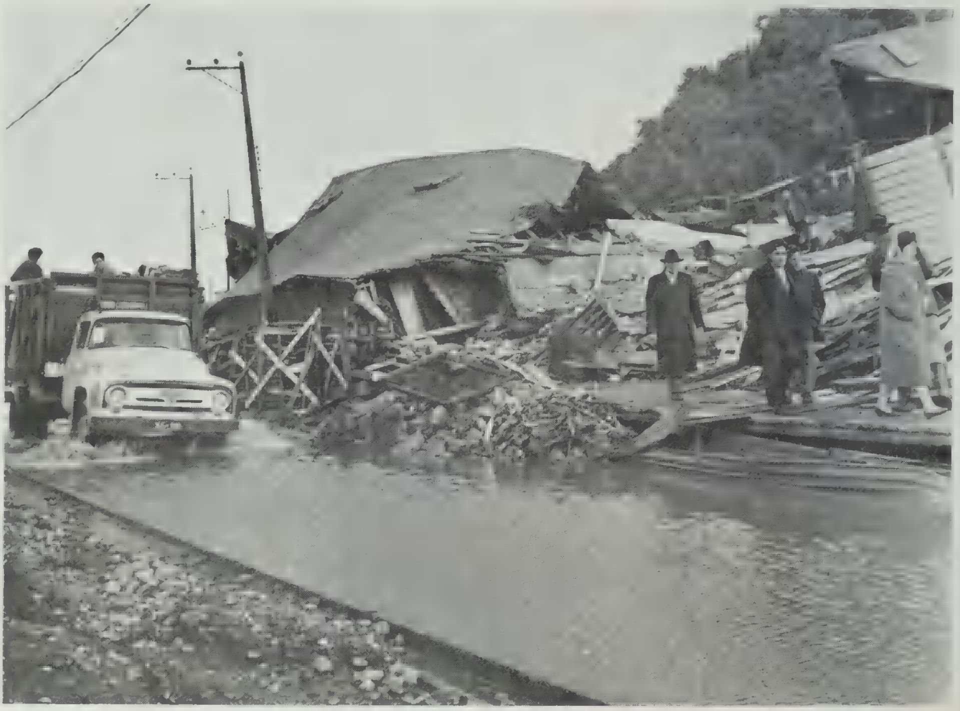

FIG. 4. Damage Near Angelmo Sector, Puerto Montt.

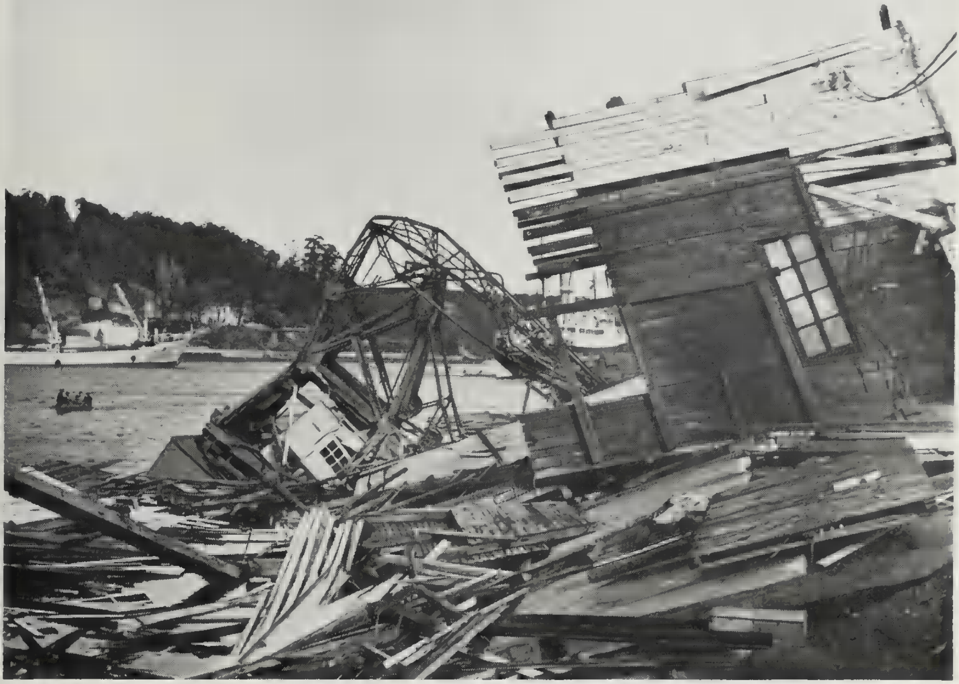

FIG. 5. Damage to Cranes and Dock Area Installations.

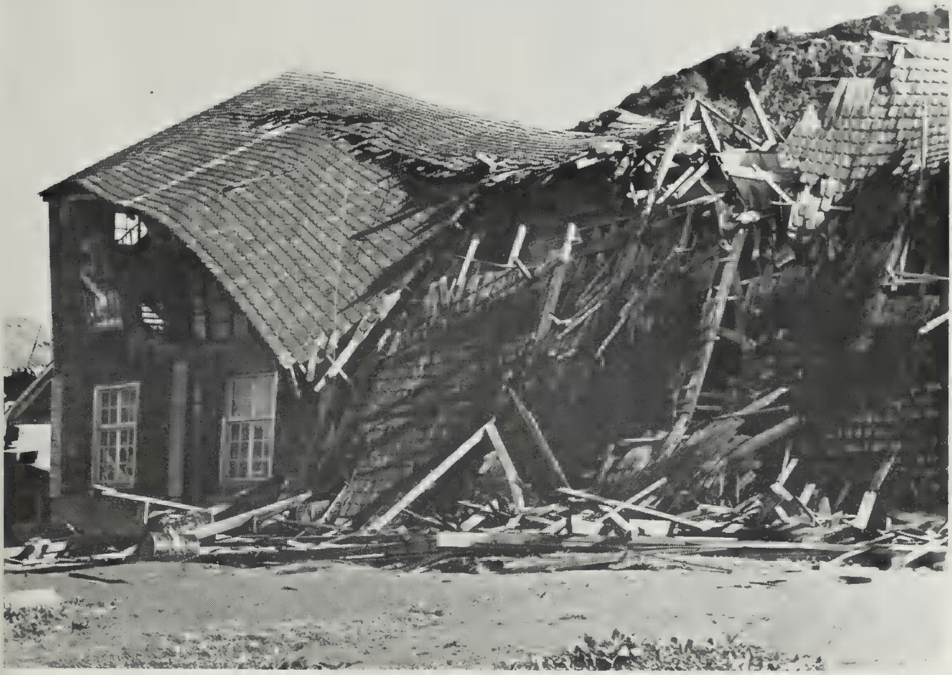

FIG. 6. Damage to Frame House at Base of Landslide.

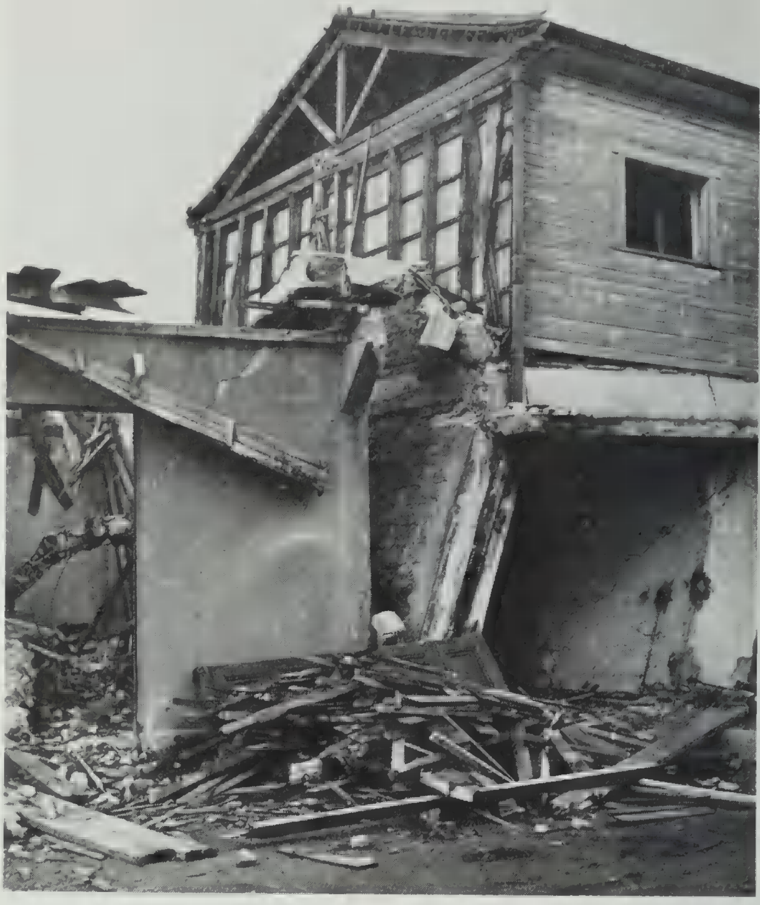

FIG. 7. House Out of Plumb.

caused separation or inclination of the foundations; (2) downslope movement of material such that the buildings were submerged, and sufficient damage was caused in some places to remove the upper part of the building from its foundations.

Areas sustained by these materials are not suitable for construction, because even though retaining walls and other methods are used to stabilize the slopes, they will continue to crack and slide through normal processes of erosion. Future earthquakes will accentuate these processes.

Deposits of Mud Flows, Debris Flows, Landslides, and Old Alluvium. Buildings constructed on these deposits were damaged in some places and not in others. The area covered by these materials south of Calle Santa Maria show less damage than those to the north of this street. This indicates that material to the south of this street is better compacted than that to the north of this street, which is nearer to the point of the origin of the earthquake. There is little evidence of damage in the area of landslide deposits west of the highway to Puerto Varas, because of the lack

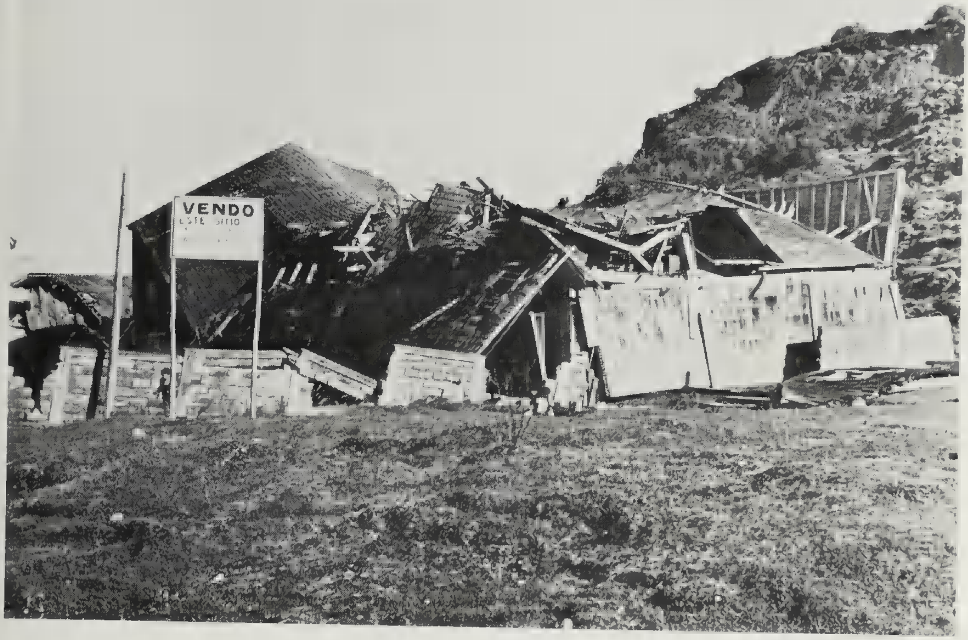

FIG. 8. Damaged Building at Foot of Landslide.

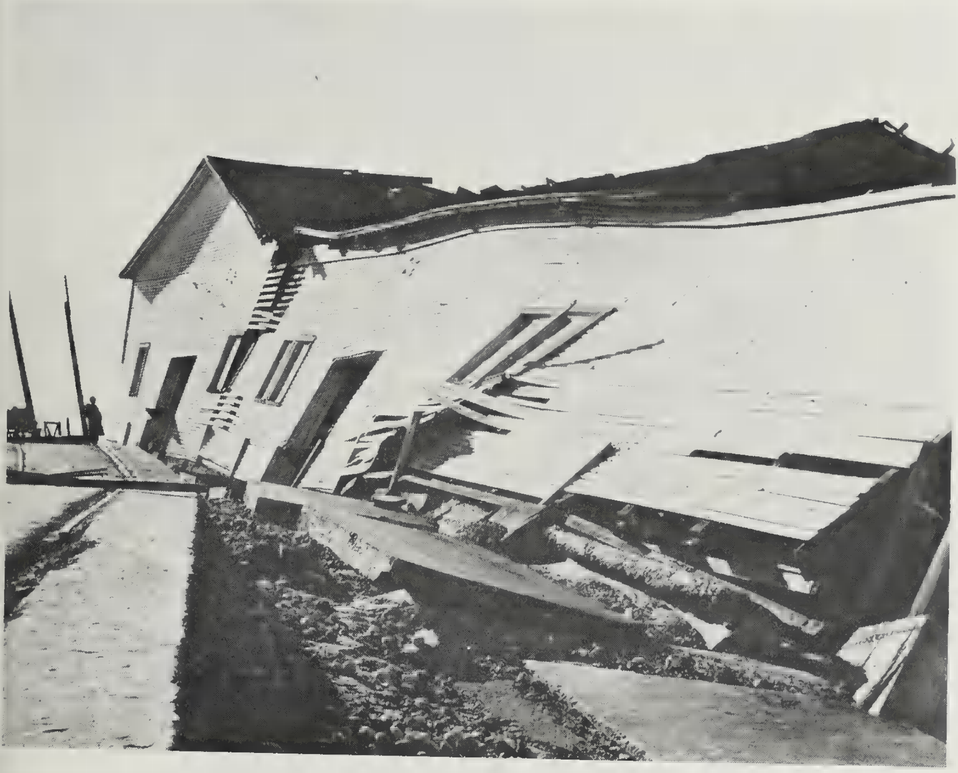

FIG. 9. Damage in Dock Area.

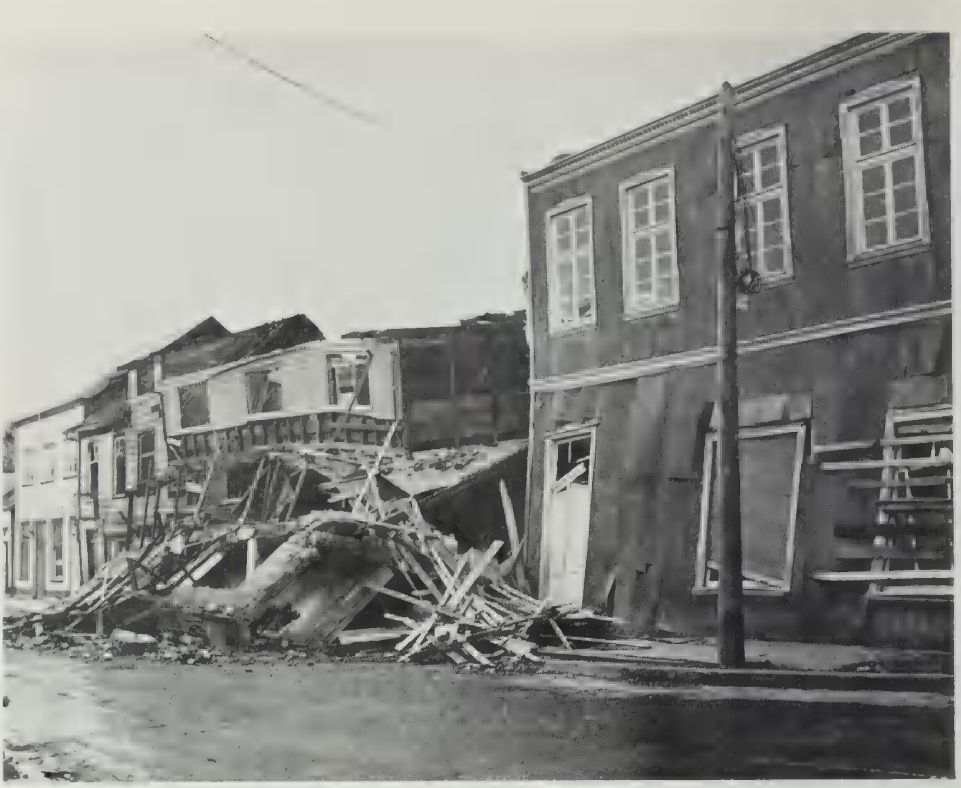

FIG. 10. Damaged Houses in Puerto Montt.

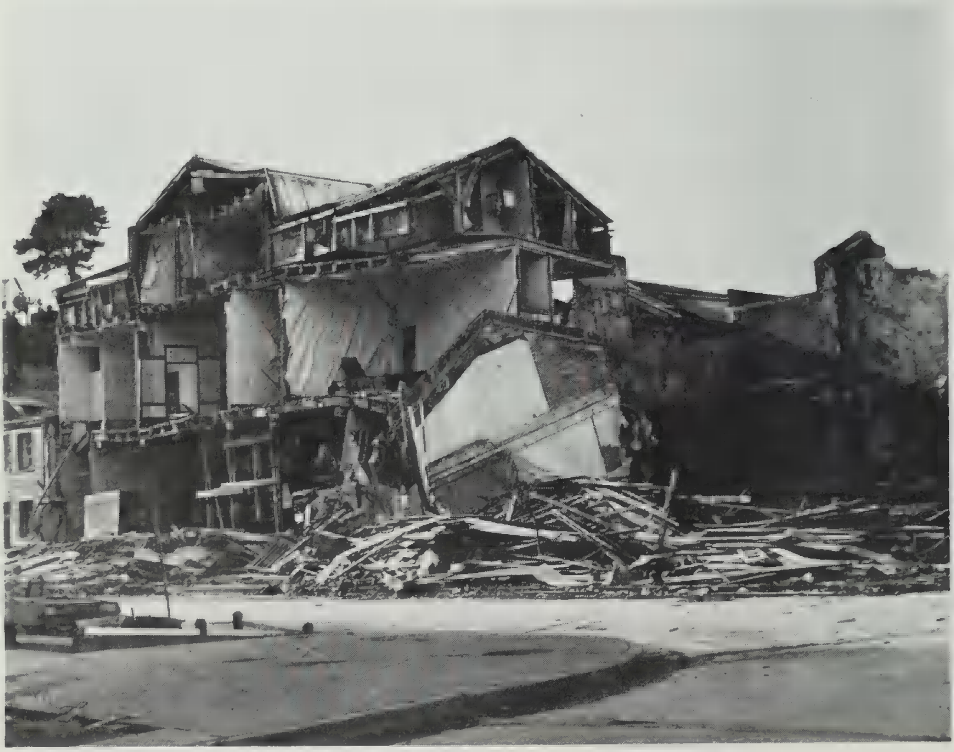

FIG. 11. Remains of a Bank in Puerto Montt.

of building; there are no fractures or other evidence of recent movements on any part of the surface.

Based on the present inadequate information, the area covered by these materials to the north of Calle Santa Maria is not a desirable area for construction. Construction should be avoided near the base of the terraces, where the steep slopes are covered by colluvium that may move and destroy any nearby structures. South of Calle Santa Maria all structures should be earthquake resistant. The landslide terrane west of the highway to Puerto Varas is adequate for one- or two-story buildings, if no evidence appears to indicate that it is again becoming active. It would be foolhardy to predict eternal stability for this or any similar area of landslides.

Debris Flow of 1957. The area covered by the debris flow of 1957 is probably not recommendable as a construction site for buildings with shallow foundations, because this material is not well compacted. If buildings are placed on foundations that reach below the base of the debris flow, they will be as secure as those based on the landslide terrane west of the highway to Puerto Montt. In the eastern part of the area covered by this debris, the fractures observed near the scarps of the deposits from the mud flow of 22 May indicate a weak condition of the soil. Construction should be prohibited here.

Mud Flow, Debris Flows, and Landslide Deposits of 22 May 1960. Areas covered by these deposits should be avoided as construction sites because some may again become active even without earthquakes.

Beach Deposits. Of the few buildings placed on beach deposits, some were damaged; nevertheless, others constructed over wooden piles were damaged only slightly.

Presumably the sea wall is constructed over these deposits; that it failed in so many places is no valid argument as to the debility of the material on which it was placed, because it obviously was not designed to resist the great lateral pressure of the dense artificial fill on the inside of the wall. Tests of bearing strength of these materials will have to precede any judgment as to the strength of these deposits for construction.

Artificial Fill. Almost without exception, all buildings on artificial fill were damaged and perhaps one half of them irreparably so. A very few of the well-constructed buildings resisted the earthquakes, as a ship might resist a tempest, but when the earthquake stopped these buildings were no longer vertical.

With few reservations it may be concluded that the artificial fill should be avoided as a construction site for small buildings. The site for large buildings and for the port should be investigated in detail to the depth necessary to determine the specifications for the erection of earthquake-resistant structures; however, this will be costly.

ACKNOWLEDGMENTS

The authors would like to recognize the hospitality and cooperation of the inhabitants of Puerto Montt. In particular, they thank Sr. Jorge Brahms, Intendente of the province of Llanquihue, as well as the mayor of Puerto Montt, the Chilean Air Force, and Sr. Elizardo Bravo S., the architect of Puerto Montt.

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STUDIES MADE BETWEEN ARAUCO AND VALDIVIA WITH RESPECT TO THE EARTHQUAKES OF 21 AND 22 MAY 1960

By Leonardo Alvarez S.

(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

The earthquake of 21 May was felt as a brusque horizontal movement; the large shock of 22 May was felt as a suave movement of large amplitude similar to a ship at sea. Lebu was extensively damaged. The shoreline at Lebu was elevated 1.5 meters, rendering docks and waterside facilities useless; a large expanse of new beach was exposed. Rio Lebu is no longer navigable because of the uplift. Details of tsunami are reported for several towns on the Arauco Peninsula and south to Tolten.

Introduction

In connection with the earthquakes that occurred on 21 and 22 May 1960, the author, in company with Roberto Morales and Arturo Valenzuela, was sent to make observations of the effects of the earthquakes in the coastal region between Arauco and Valdivia. Observations were also made of the magnitude of the maremoto at different points on the coast. The commission, directed by the author, left Santiago on the 25th of May, stopped overnight in the locality of Los Angeles (110 km east of Lebu) and went to Lebu, passing by Cañete (figure 1). Leaving Lebu, 3 days were spent traveling to Arauco and Lota, briefly visiting Curanilahue and Pilpilco. Later, the commission continued south, to Pto. Saavedra, Tolten (figure 2) and Valdivia.

All persons interrogated agreed that the earthquake of 21 May had brusque, ample movements of a horizontal variety, and the earthquake of 22 May was of suave, large movements such as those of a ship on the high seas, and was of a long duration. All of the earthquakes thereafter had more or less brusque, horizontal movements. By personal observations of aftershocks during our stay in Lebu, the preferential direction of the initial movements of the P waves was N10°W.

Little destruction was observed in Collipulli, 90 km east of Cañete. In the Fundo el Salto, located 16 kilometers to the southeast of Collipulli, the movement of 21 May had a preferential direction of N15°W, as indicated by the displacement of furniture in the house of the patron, the fall of the chimney and of the north wall of the house. The owner of this fundo described the seism of 21 May as undulatory, with large horizontal movements. He reported seeing waves in the surface of the "trumao" (a local name for the reddish clay-like soil produced by the weathering of the underlying rock, characteristic of the south of Chile).

Lebu Area

The commission arrived at Lebu on the 27th of May and stayed in the house of the administrator of the Victoria Coal Co. of Lebu. This house did not suffer much damage. It was constructed over concrete foundations and located on a slightly inclined terrain of sedimentary rocks of Tertiary age. The walls were panels of a network of laths covered with clay and papered. From some of the walls, the mud and paper fell; and on others, one could only see cracks in the paper, which crossed the horizontal at 45 degrees. The fall of tiles and chimneys was principally toward the east, and the second story of the house had moved 20 to 30 centimeters (with respect to the first floor) in a northerly direction (figure 3).

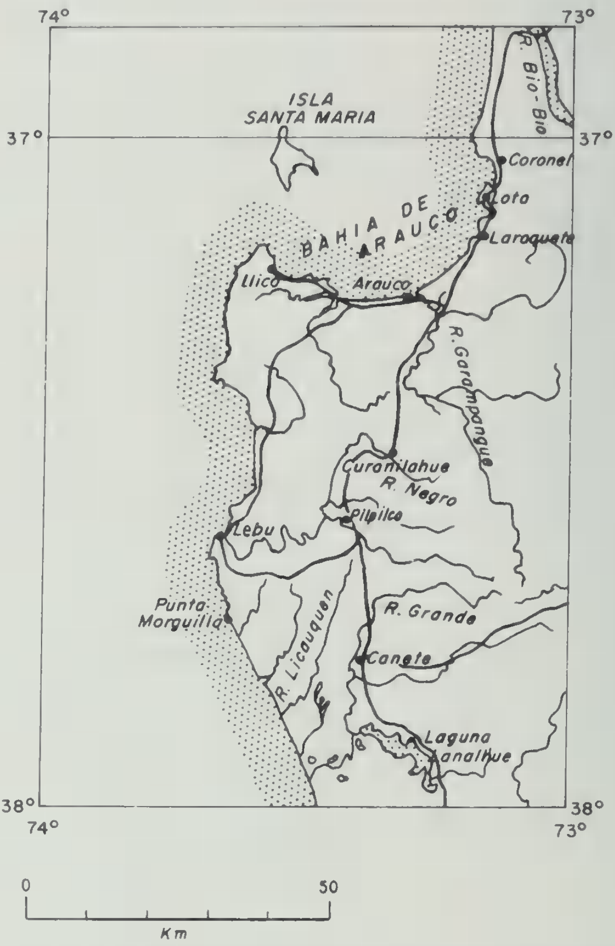


FIG. 1. Northern Sector Visited by the Commission.

In Lebu, there was considerable destruction (figure 4–7), and only the new buildings did not incur damage; for example, the new school.

The most important effect of the earthquakes in the Peninsula of Arauco was the elevation of the continent at Lebu of $1\frac{1}{2}$ meters. This elevation was measured on a post that serves to indicate the tides; the post had been established for many years in firm rock of Tertiary age. The uplift manifested itself in the following manner: (1) The level of the present high tide is now located at the level of the former low tide, the difference between the levels being about 1½ meters, and (2) the sea has retired from the beach, leaving uncovered a new beach of an average width of 50 meters all along the coast of the bay of Lebu (figure 8–10). In Arauco, one could not measure this uplift exactly, but on the coast of Lota a continental uplift of 40 to 50 centimeters was noted. To the south of Lebu, some 25 kilometers from Morguilla, it was noticed that the level of the sea was 1.5 to 1.8 meters lower than before the earthquakes. This calculation was based on a measurement, by Brunton compass, between the level of the present high tide and that of the high tide before the earthquakes. The beach is 20 to 30 meters wider than before.

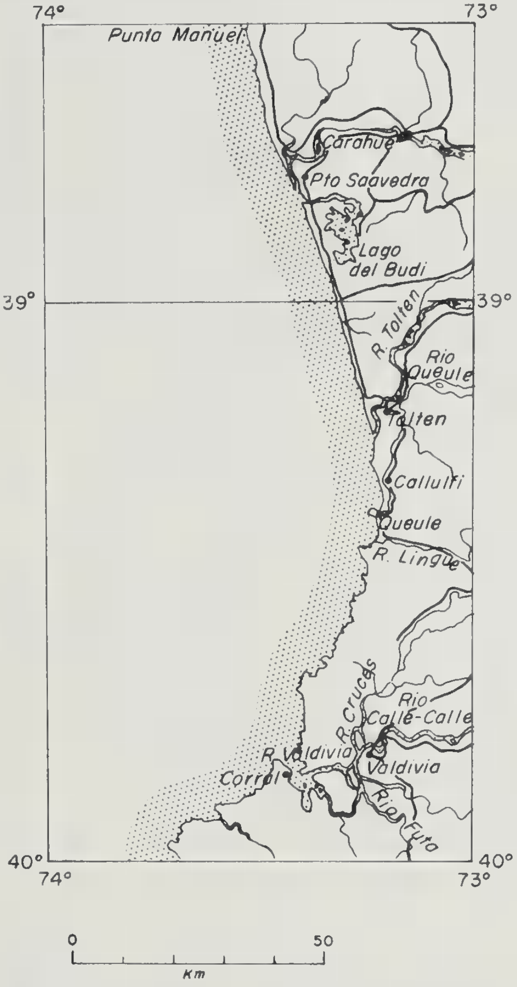


FIG. 2. Southern Sector Visited by the Commission.

On the beach, polygonal cracks were observed in the sand, especially in places

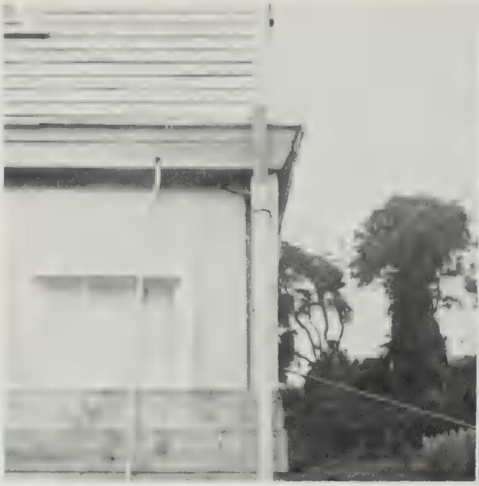


FIG. 3.

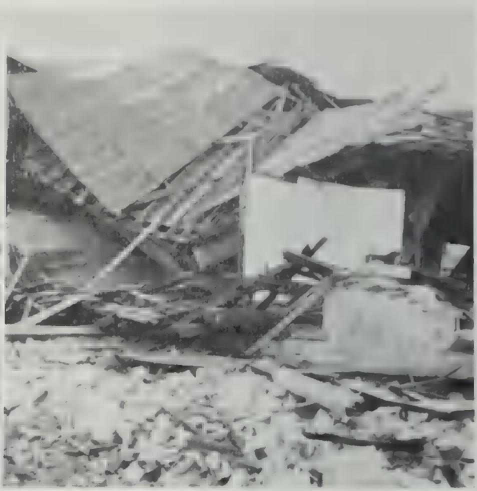


FIG. 4.

FIG. 3. House of the Manager of the Victoria Coal Co. of Lebu. The second floor slipped about 20 to 30 cm. over the first floor. The house was constructed over firm but slightly inclined land.

FIG. 4. Public School No. 22, Lebu, Which Fell on 21 May 1961. The walls fell toward the north and the roof toward the south. Construction was of brick united with a mixture of cement and sand with a good deal of lime, and no reinforcement.

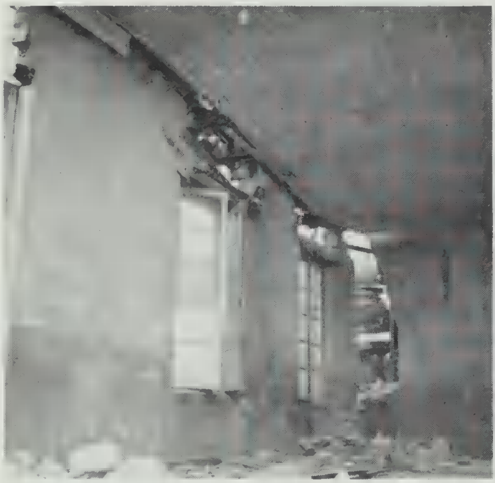


FIG. 5.

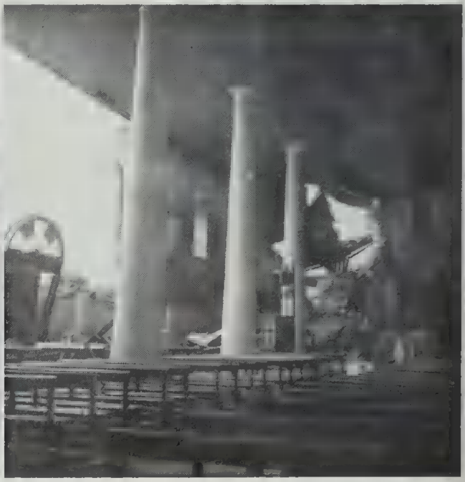


FIG. 6.

FIG. 5. Intendencia of Lebu. The second floor fell, destroying the juncture with the walls. Construction is similar to that of the building shown in figure 4.

FIG. 6. Church at Lebu. The major axis of the church is located north-south. The walls fell, in general, toward the north and the bell tower toward the south. The columns survived because they are of concrete reinforced with rails. The mortar used was cement with sand and lime.

where trees grew. These cracks were aligned in a general direction N30°E and N50°W. In a poorly cemented conglomerate, probably of upper Tertiary age, with round clasts of some 2 centimeters in diameter, numerous landslides with a few cracks N20°E to N30°E were observed. Some 3 to 5 kilometers to the interior from this part of the coast, in the Fundo Quinahue, there were cracks in the "trumao" of several hills; they were found on the western side of the summits and were in line in the north-south direction. They had directions that varied between N10°E and N10°W, with a variable extension between 50 and 200 meters, widths of $\frac{1}{2}$ to 30 centimeters, irregularities in their surface of 1 to 15 centimeters, and depths of perhaps 50 centimeters.

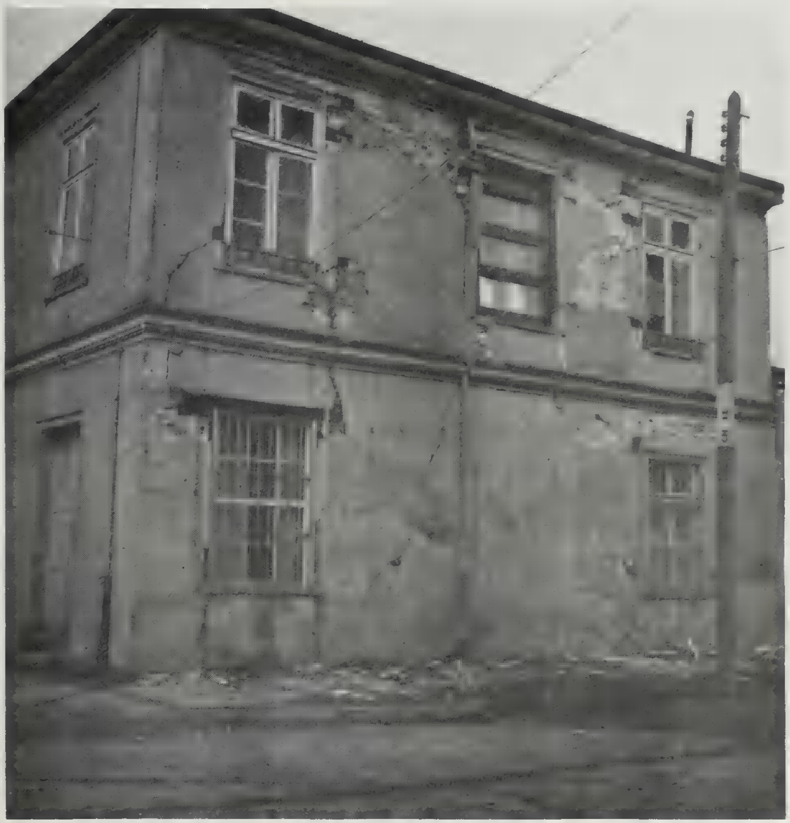
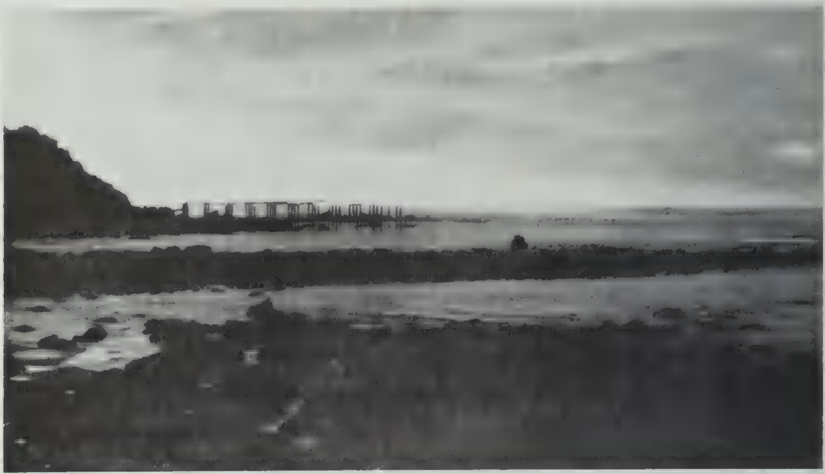


FIG. 7. House in Lebu Destroyed in the Same Way as the Church in fig. 6. The window panes are broken and the walls are cracked, with sets of shear fractures running about 45 degrees to the vertical. The house is uninhabitable.

On the northern edge of the beach of Lebu there were large landslides along the cliffs in rocks of Tertiary age. The effects of the tidal waves on these also may be observed. One is able to see that the water reached a height of 5 or 6 meters above the normal level.

The Lebu River was visibly affected by the uplift of the continent: it is shallower than before, and boats are no longer able to navigate the river, a thing that they did before without difficulty. The north half of the bridge (direction N30°E) over the the Lebu River was displaced 10 centimeters with respect to the other half, measured at the central junction of the bridge. (The sense of displacement was not recorded.) In the mouth of the Lebu River, there were cracks in the recent fill with the direc-



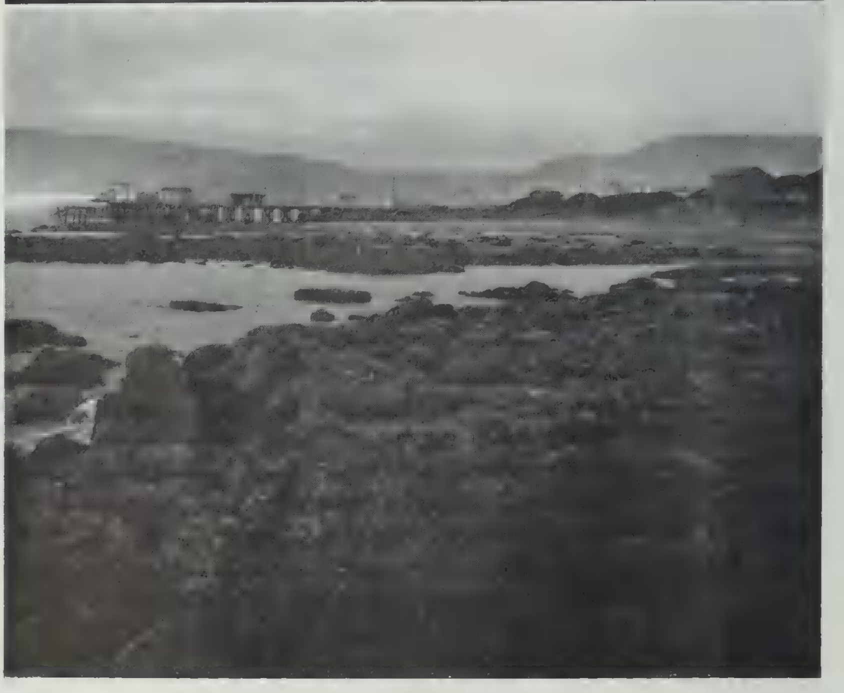


FIG. 8. Effects of the Continental Uplift, New Beach at Lebu. The continent rose about 1.5 meters.

FIG. 9. Effects of Continental Uplift, New Beach at Lebu.

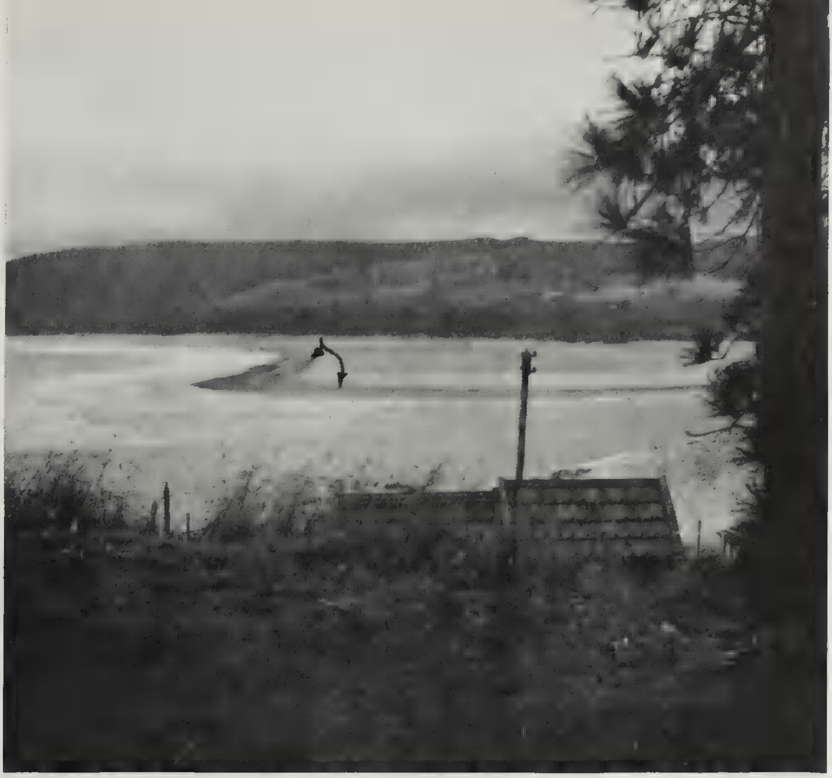


FIG. 10. Mouth of the Rio Lebu. The arrows indicate the former high tide level.

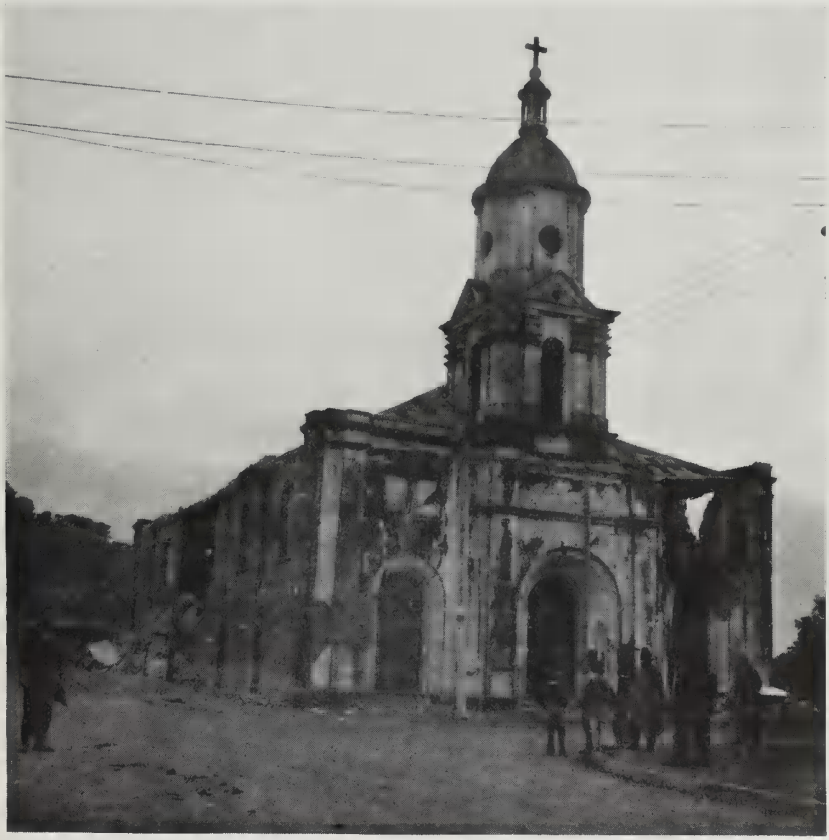


FIG. 11. Church at Arauco. The only part that did not incur great damage was the bell tower, built before the construction of the church. The tower was made of reinforced concrete, and the rest of the church was made of brick with a mortar of cement, sand, and lime.

tions N65°W and N45°W. Some of these cracks were about 1 meter in depth, but their width was not more than 5 centimeters.

CURANILAHUE

In Curanilahue, there was a much higher percentage of destroyed buildings. All the ancient buildings suffered considerable damage, but new constructions were not affected by the earthquakes. The bridge at the entrance south of Curanilahue was cracked, and its base of concrete has fallen towards the east.

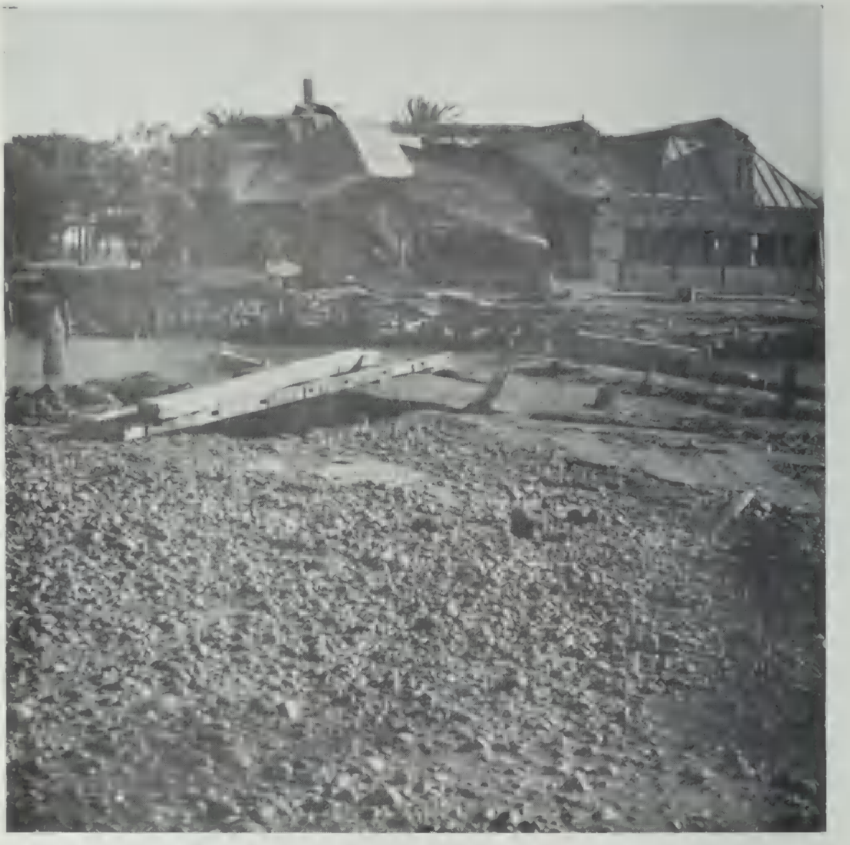


FIG. 12. Effects of the Earthquakes and the Maremoto in Puerto Saavedra. The stony soil was produced by the action of the sea upon a fluvial soil about 0.5 meters in depth.

PILPILCO

Pilpilco did not incur much damage, and the mine there is functioning almost normally. There were landslides in the hills but without any serious consequences, and the activity of the region was normal.

ARAUCO AREA

About 80% of the construction in Arauco incurred some damage (figure 11). Nevertheless, and in spite of the strong seismic movements of the earthquake,

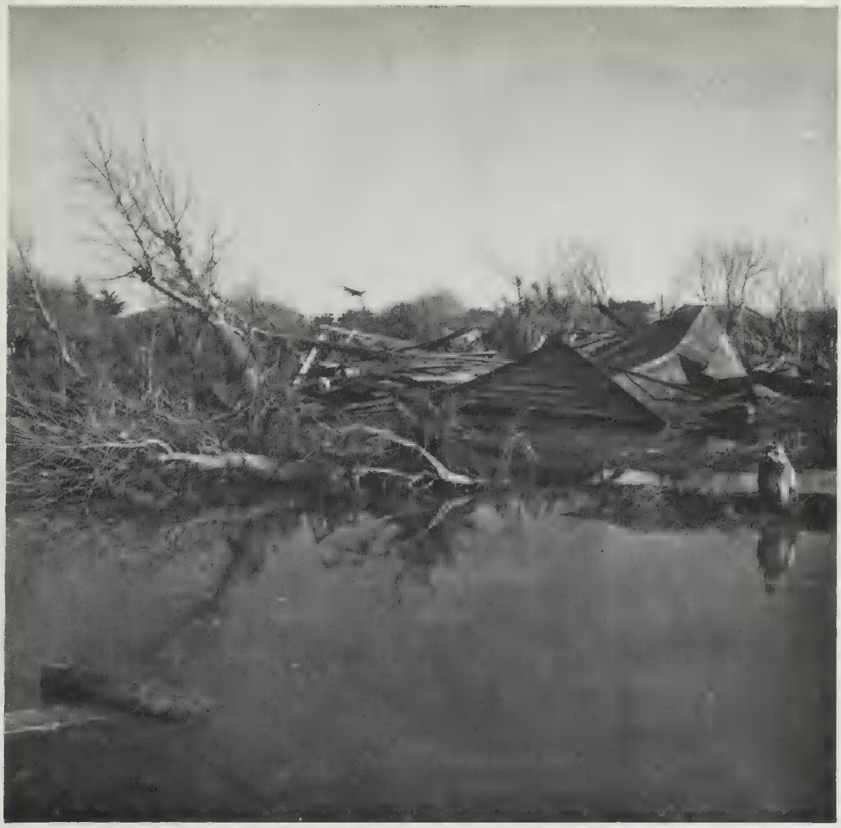


Fig. 13. State in Which the Majority of the Homes in Puerto Saavedra Were Left after the Maremoto. The water remained, in many places, at depths in excess of 20 cm.

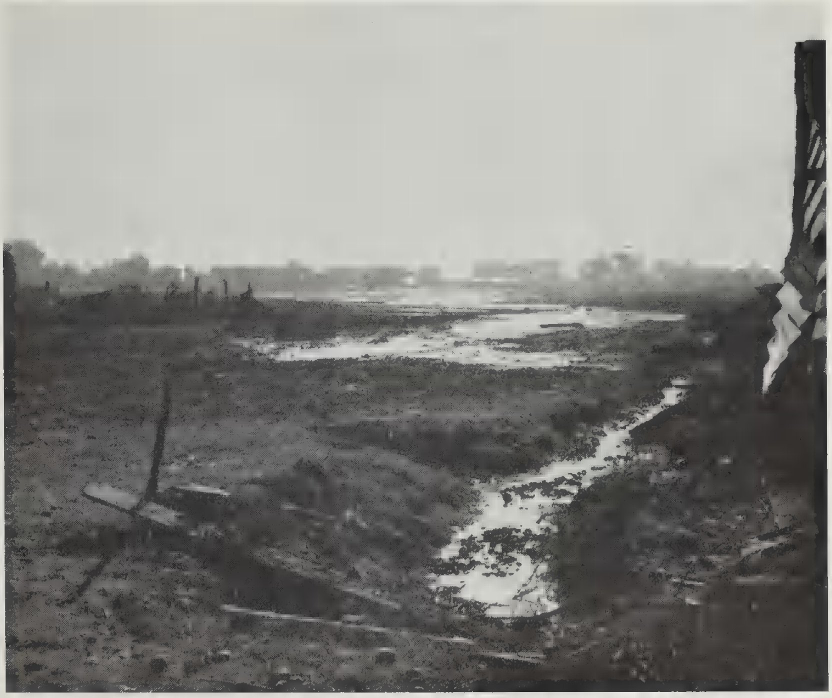


Fig. 14. Center of the Town of Puerto Saavedra. All the houses were carried away by the sea, some between 1 and 2 kilometers inland. Here also may be noted the washing away of the soil, leaving a stony terrain exposed to view.

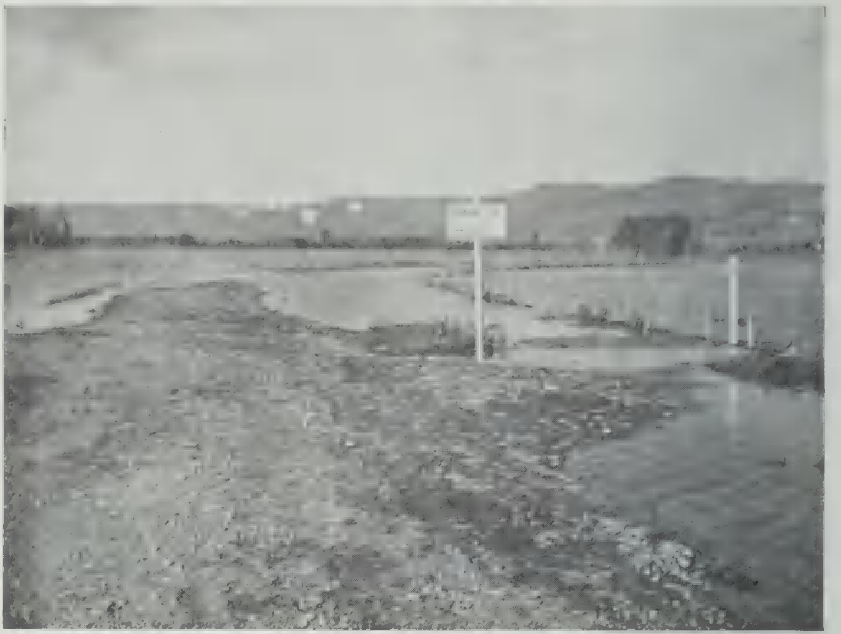


FIG. 15. Road to Queule by the Fundo los Boldos. The road was inundated by 30 cm. of water. Communication with Queule could be made by river only.

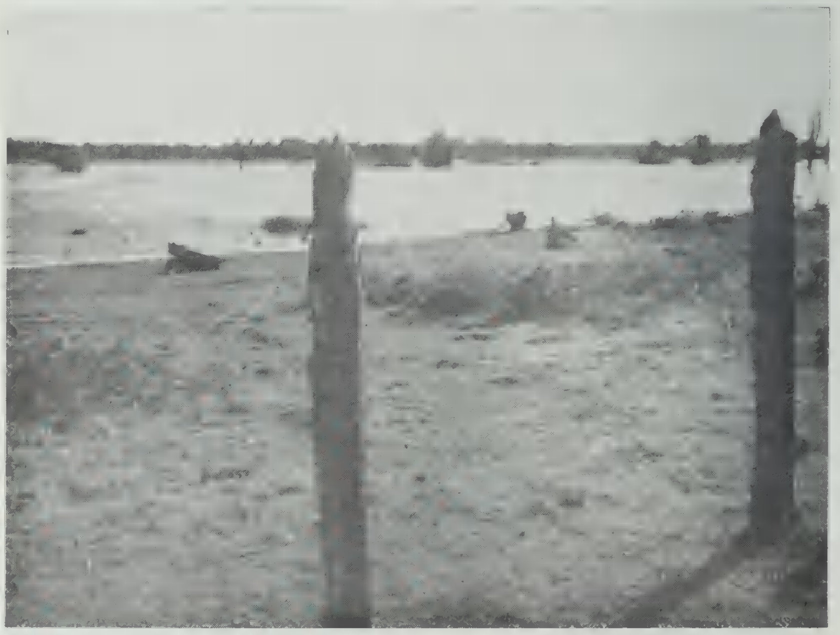


FIG. 16. Road to Queule. Cultivated fields and pastures inundated by the sea. The water remained between 0.5 and 1 meter in depth.

statues and posts in the city remained standing. On 21 May the movement was of preferential direction N60°E, and also perpendicular to that direction. The inhabitants of Arauco indicated that there was a brusque vertical movement. The destruction was caused by the horizontal movements, which threw down walls, roofs, and furniture. In the government house a heavy strong box fell from its pedestal.

In Arauco, the sea wave occurred on Sunday, 22 May, at about 1830 hours. The sea advanced slowly for a distance of 700 to 1,000 meters up the extensive beach without any destruction of houses, which were a considerable distance from the beach. The water only flooded the floors of the houses, without carrying them away. In this locality, a previous retreat of the sea was not observed as in the rest of the localities visited. Nevertheless in Llico, all the buildings were destroyed; and in Laraquete, there was about 70% destruction according to information obtained from the Carabineros and from the governor.

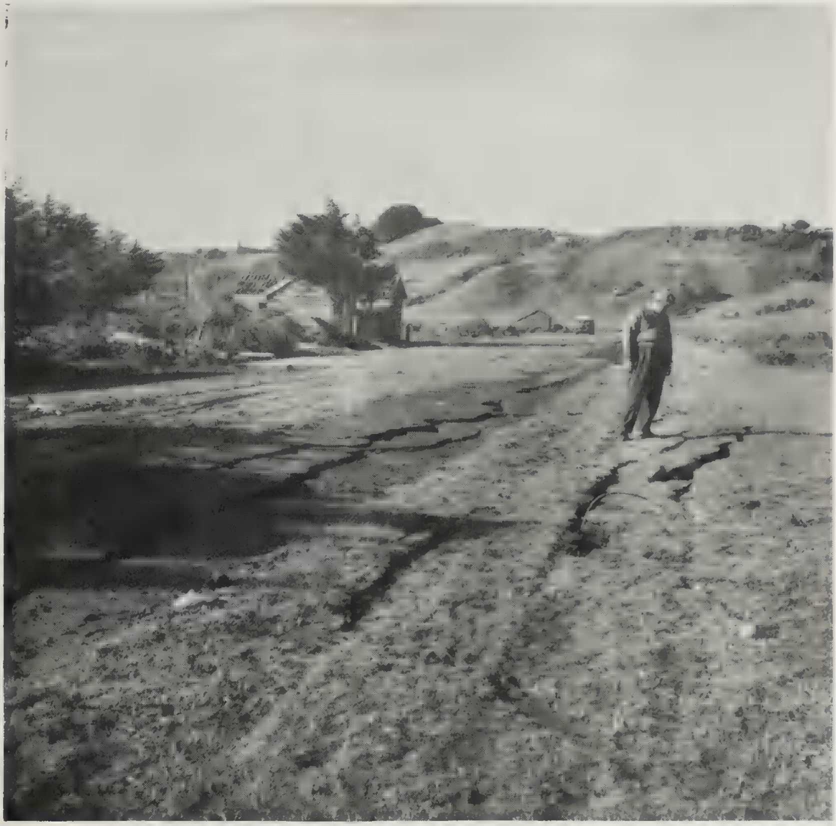


FIG. 17. Subparallel Cracks on the Flood Plain of the River near Tolten.

PUERTO SAAVEDRA AREA

The commission went to Puerto Saavedra on 30 May. This village was totally washed away by the waters of the sea wave of 22 May, but with little loss of life or

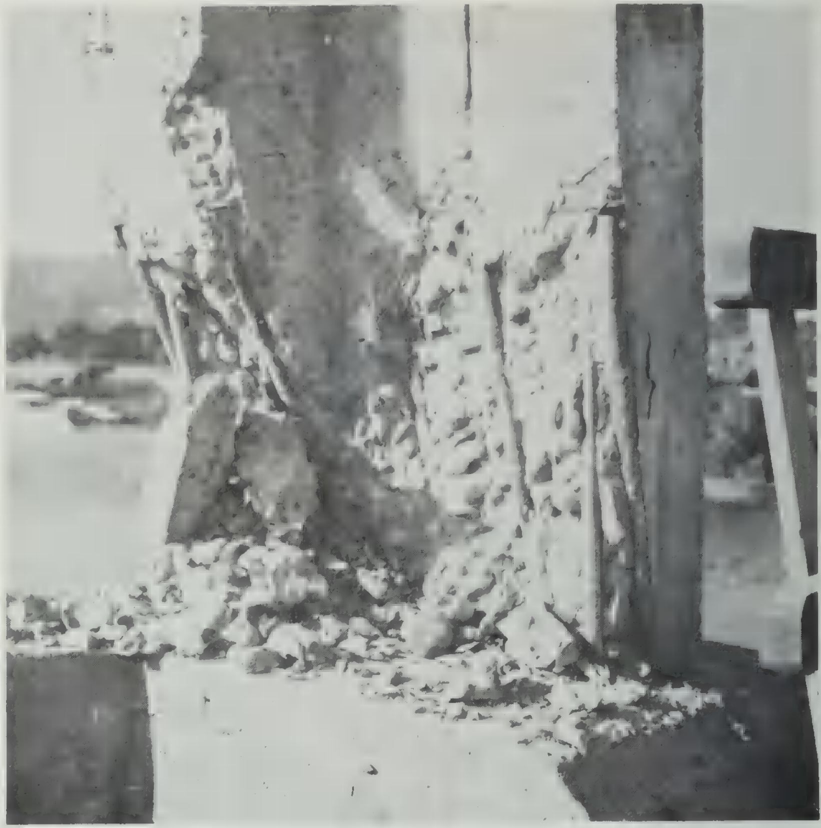


Fig. 18. Pillars of the Hanging Bridge over Rio Tolten. The reinforced concrete of which this bridge is constructed is not of good quality.

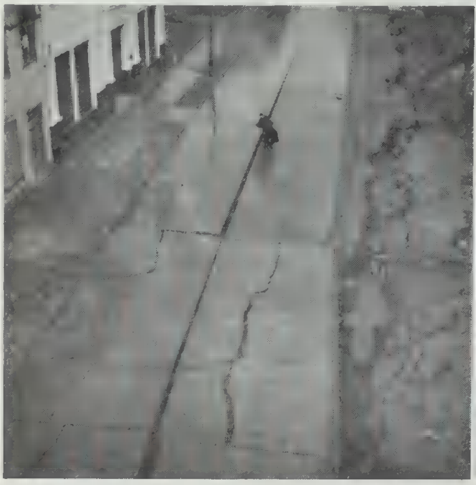


Fig. 19.

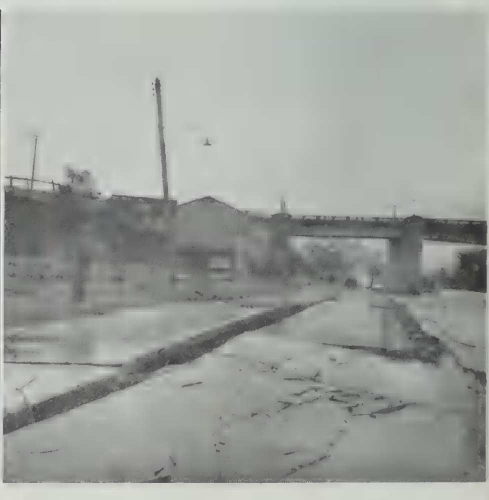


Fig. 20.

Fig. 19. View of the Valdivia Riverfront Promenade from the Bridge Pedro de Valdivia. The cracks were produced by the sliding of the soil toward the river.

Fig. 20. State of the Waterfront of the Rio Valdivia After the Earthquakes. The cement slabs were partially broken and slid as units as well.

injury because of the slow onset of the first wave, permitting the populace to seek higher ground. There were three advances of the sea, with the third carrying away the houses and animals. The sea flowed approximately 5 kilometers inland, carrying several houses for 3 or 4 kilometers and leaving them in the middle of the fields. The water reached a level of approximately $2\frac{1}{2}$ meters above its natural level (figures 12–14). The off-shore bar, or spit, that deviates the flow of the Rio Imperial from the original east-west course to one north-south was broken by the tidal wave in the northern part where it was joined to the continent, leaving the southern part transformed into an island. (Translator's note: For a more complete description, see report by Wright and Mella.)

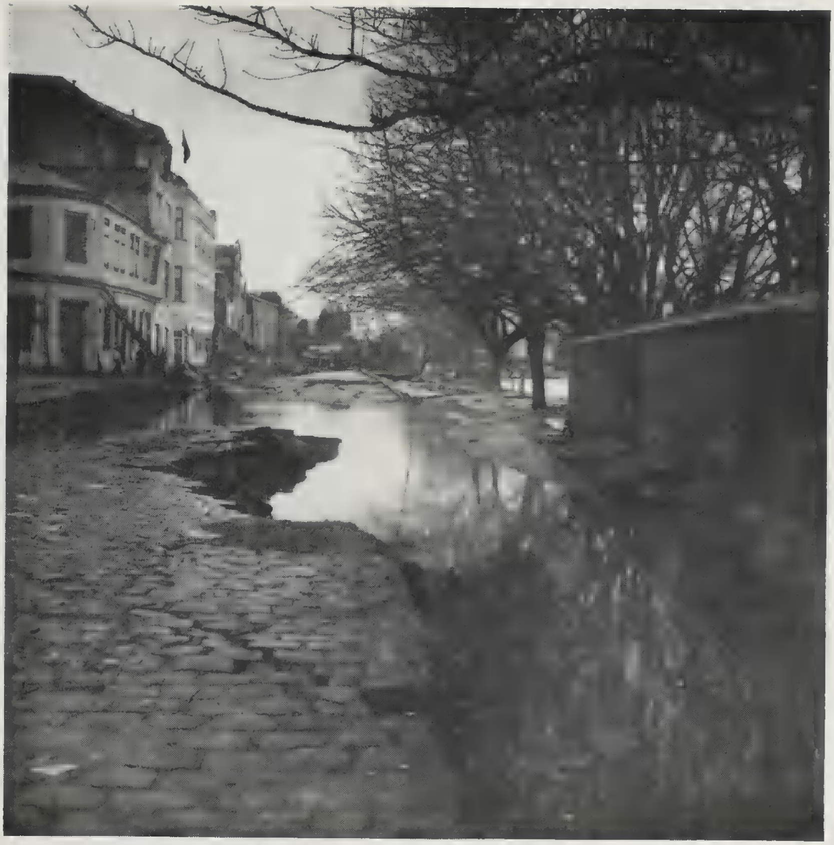


FIG. 21. Sinking of the Terrain in Valdivia. The structure to the right sank about 1.5 meters.

TOLTEN AND QUEULE AREAS

In Tolten, where the water ran about 3 meters above the normal level of the river, there had occurred seven waves of the water. The first rising was at about 1545 hours, Sunday. The second, at 1645 hours, was the biggest, and it flowed inland approximately 4 kilometers from the coast to the locality of Callulfi. This produced inundations in the Fundo los Boldos (figure 15), which ruined the road that leads to Queule (figure 16), a coastal pueblo that was completely carried away by the water. In the Fundo los Boldos, water remained, on 31 May, at a depth of about ½ meter.

In the alluvial terrain that surrounds Tolten, a few cracks, some 15 centimeters wide, were produced in the preferential direction N25°E, with some minor cracks perpendicular to them (figure 17). The swinging bridge between Queule and Tolten, across the Rio Tolten, failed because of the displacement of its foundations produced by the movement of the soils affected by the earthquake. The reinforced concrete pillars of a firm mix were bent about 30 centimeters from the base. Fragments spalled off, leaving the twisted reinforcing irons visible (figure 18). The commission could not go to Queule because of the disappearance of the road below the waters, and because launches were not available for crossing at this time.

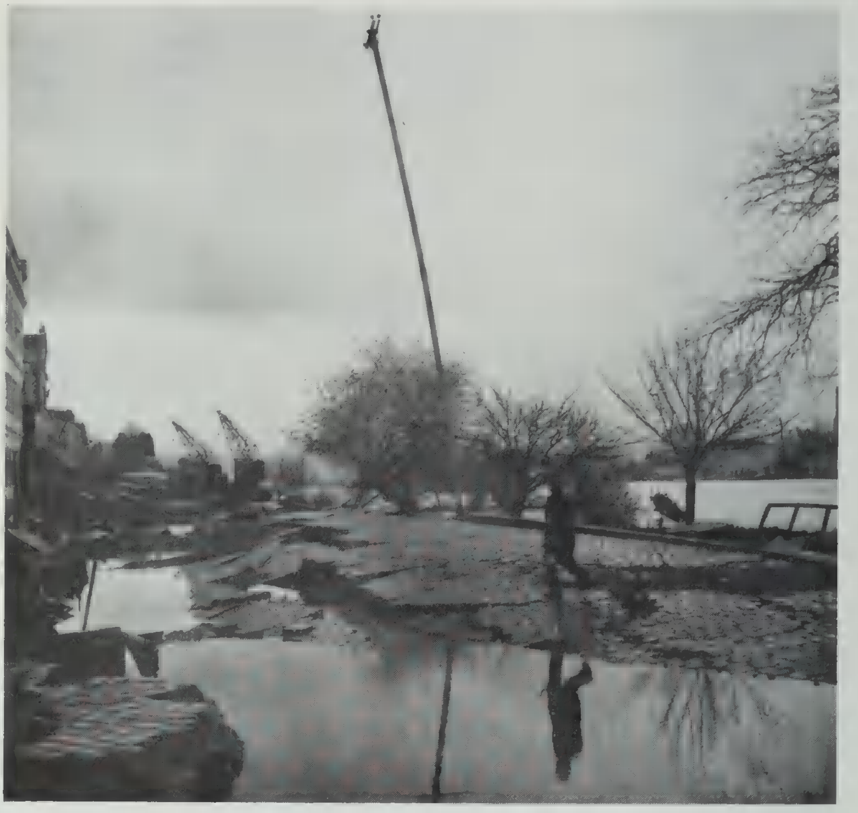


FIG. 22. Distortion of the Quay along the Valdivia Riverfront.

VALDIVIA AREA

On Tuesday, 1 June, the commission arrived in Valdivia. In this city, the destruction was produced principally along the edges of the rivers Valdivia and Calle-Calle.

There were numerous landslides in the direction of the river from the banks (figures 19–22), and many houses were put out of plumb by compaction of the sediments over which the city was constructed. The terrain in the center of the city sunk $1\frac{1}{2}$ to 2 meters. The bridges that cross the rivers Valdivia and Calle-Calle were destroyed at their extremities, because the concrete of which they were constructed failed; in part because of tension produced by the seismic movements, and in part because of the sliding of the margins of the rivers, so that the pillars were tilted, creating a horizontal component of tension that destroyed the concrete. The pillars in the center of the bridge Pedro de Valdivia were not damaged, nor were those of the bridge Calle-Calle (figure 23).

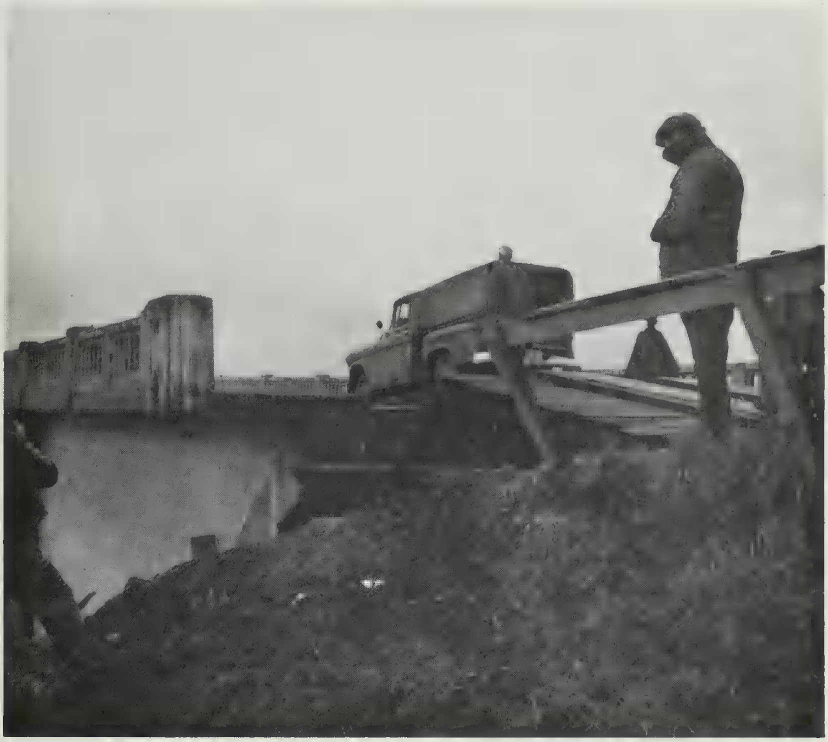


FIG. 23. Approach to the Pedro de Valdivia Bridge from Isla Teja.

The great drinking-water tank, which is about 100 meters from the regional hospital, and which fortunately was empty during the earthquake, showed shear cracks in the structure of its pedestals. These shear cracks crossed each other at approximately 30-degree angles. At a level about $\frac{1}{5}$ the height of the tank, there were many horizontal cracks.

In Valdivia, the level of the river increased about $1\frac{1}{2}$ to 2 meters, probably caused by the sinking of the continent. The cracks that were seen in the lands near the river were caused by the sliding of water impregnated sediments by the impulses of the earthquakes.

CONCLUSIONS

The most outstanding effects of the earthquakes were in the coastal region between Arauco and Valdivia. The great coastal block moved, as on a hinge, with an uplift on the Peninsula of Arauco of about 1.3 to 1.5 meters and, to the south, a sinkage of about 1.5 to 1.8 meters on an east west axis, located between Lebu and Pto. Saavedra.

Superficial evidence of active faults was not observed.

The destruction of buildings increased from north to south, betwen Chillan (175 km northeast of Lebu) and Valdivia. The destruction was greater in buildings recently constructed over unconsolidated sediments, artificial fills, and inclined lands such as on the banks of the river and on the coast. The buildings on firm rock and flat land did not suffer greatly.

On the Mercalli scale, the intensity of the greatest earthquake of the series was approximately IX in Valdivia, VIII in Lebu, VIII in Curanilahue, and VII in Arauco. In the localities washed away by the waters, it was impossible to calculate the intensities.

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RELATION BETWEEN THE GEOLOGY OF VALDIVIA, CHILE, AND THE DAMAGE PRODUCED BY THE EARTHQUAKE OF 22 MAY 1960

By William W. Doyel, Aldo Moraga B., and Eduardo Falcon M.

ABSTRACT

A study was made to determine the relation between the damage caused by the earthquake of the 22nd of May, 1960, in Valdivia, Chile, and the geology of the city. A geologic map and an investigation of the damage was made. There was no evidence in the area of fault movements produced by the earthquake. The inundation of extensive areas of Valdivia and its environs are attributed more to compaction of Recent sediments than to a general sinking of the coast. Valdivia is situated in the basin of the Rio Valdivia. The geologic formations that crop out there are composed of Pleistocene and Recent sediments. Six mapable units have been selected for the preparation of this report. The great part of the damage in the city of Valdivia was caused by defective construction; nevertheless, the greatest damage is observed in areas where Unit QV 6, Recent alluvium or artificial fill, crops out. More detailed geologic studies should be made upon which to base construction and future planning. The studies should be complemented by drilling, gravimetric investigations, and soil studies.

Introduction

Object and Method of Investigation

On Sunday, 22 May, 1960, a little after 1500 hours, an earthquake of magnitude $8\frac{1}{4}$ on Richter's scale caused great damage along the length of the south-central region of Chile, which includes the city of Valdivia. The Ministry of Public Works asked the Instituto de Investigaciones Geologicas (I.I.G.) to begin studies in the most affected cities to determine the relations between the geology and the damage. As a result of this petition, the I.I.G. sent the authors to Valdivia.

The authors completed the field investigations between the 15th of June and the 15th of July. Ernest Dobrovolny and Richard Lemke, geological engineers of the U. S. Geological Survey, and Robert Dingman, geologist of the U. S. Geological Survey (U.S.G.S.) stationed in Chile, visited the city between the 6th and 10th of July.

This report is based on a preliminary geologic reconnaissance of Valdivia and its suburbs. A map was made of the superficial geology of the urban area, bringing together the available informaton relative to the subsoil. A reconnaissance was made of the damage to determine its location and extension. These data are here combined and correlated.

The topographic base for the making of the map (figure 1 in the pocket at the back of this issue) was a plan on the scale 1:5,000 of the Direcion Central de Estadistica y Census. Aerial photographs taken by the Chilean Air Force were used for tracing some geologic contacts.

Description of the Area

The city of Valdivia (figure 2), population 57,262, capital of the province of Valdivia, is located on a curve some 20 km from the mouth of Rio Calle Calle.

Principal industries of the city are leather, shoemaking, beer, and ceramics. It is an important center for the shipping of agricultural produce, livestock, and wood.

Normally, the maritime transport routes, railways, highways, and air routes give access to the city. Because of the earthquake and subsequent inundation, the railways were cut and the roads became scarcely usable.

The commercial district and the major part of the residential area of Valdivia are on the south bank of the river. The sector along the north bank of the river, known as Las Animas, has some residences and properties of importance. On the eastern side of Isla Tejas, along the Rio Calle Calle, there are houses and factories. The rest of the area is utilized for agricultural purposes. The Universidad Austral is located at the extreme northeast of the island, at the confluence of the Rio Calle Calle and the Rio Cau Cau.

Relief Drainage and Climate

Valdivia lies in a basin containing parts of Rio Cruces and Rio Calle Calle. This basin is bordered towards the north by a transverse range of hills that forms the hydrologic divide of the Rio Tolten from the Rio Valdivia, and by the chain of coastal hills. These latter form a range, some 600 meters in altitude, bisected by the Rio Valdivia in front of Corral, and continue feebly southward as the Altos del Mirador about 300 meters above sea level.

Towards the southeast of the city, the hill Huichahue (640 meters) slopes towards the valley of the Rio Valdivia and determines the course of the Rio Fujan and the Rio Angachilla.

The city itself is situated on a terrace between 10 and 15 meters above mean sea level. This terrace has been dissected, but many of the ancient canals are no longer active, having been filled with alluvium and artificial fill. Almost all of the valley was once covered by this terrace, as indicated by remnants in other parts of the city. The major part of the drainage canals are in the form of U's with short laterals about 10 meters above the generally swampy flood plain.

The Rio Valdivia begins at the confluence of the Rio Cruces and the Rio Calle Calle, which unite to the west of the city. The Rio Cruces enters the basin from the northeast, forming, with an arm of the Rio Cau Cau, Isla Tejas. Tides of more than a meter are noted in the Rio Valdivia.

The average mean temperature of the city of Valdivia is 11.8°C, with a range of 8.9°C. The warmest month is January with 16.7°C and the coldest month July with 7.8°C. The average annual rainfall is 2.5 meters. The major part of the precipitation falls between April and September. The rest of the year is drier; the rainfall of 63.5 mm in January and 67.1 mm in February are not considered great enough to qualify these months as wet!

GEOLOGY

Previous Studies

Dr. Juan Brüggen (1950) describes some of the geologic aspects of the area of Valdivia. Walter Wetzel, Professor of Geology at the Universidad Austral of Valdivia, made a detailed geologic map covering a zone approximately 43 km by 23 km that included the city vicinity, and is preparing a report to accompany the map.

Engineer Sr. Juan Karzulovic (1960) published a report on the subterranean water resources of the area of Valdivia in which he gives geologic information about the subsoil based on drillings made by ENDAS.

Regional Geology

Metamorphic Rocks

The major part of the outcrops in the area of Valdivia are of the metamorphic complex that extends along the Pacific coast from the province Colchagua to the province of Chiloe. Wetzel has mapped the metamorphic rocks in and around the basin of Valdivia as constituting the principal material of the hills and the valleys.

The authors observed this formation towards the northeast of the city and on the Cuesta de Santa Elvira. Here it is a mica schist whose plains of exfoliation dip 15 degrees to 25 degrees towards the southeast and are crossed by fractures trendng N80°W and some quartz veins of small thickness having the same direction. In the wetter zones the mica schists have been limonitized, passing gradually from rock into reddish coffee-colored mud that forms a soil over which the vegetation rests.

The metamorphic rocks probably underlie all of the topographic basin of Valdivia. A well was drilled by ENDAS at the intersections of Calle Picarte and Calle Huemul, to a depth of 127 meters, where decomposed rock was reached.

Sedimentary Rocks

Piso Navidad: A formation of Middle-Tertiary age that Wetzel and other authors correlate with the Piso of Navidad is located discordantly over the metamorphic complex. The outcrops of these sediments are irregularly distributed in the area, found on the hills, and form, in places, slopes that fall gently to the valley. In the road to the south, 5 km from the city limits, there are outcrops of this sedimentary formation, principally composed of laminated clays and boulders up to 20 cm in diameter, that contain an abundance of marine fossil fauna.

Pleistocene Deposits: Some outcrops of morainic and fluvioglacial sediments occur in the area of Valdivia. These are isolated erosional remnants, generally located on the sides and summits of the hills. These materials are probably Lower- and Middle-Pleistocene deposits. Upper Pleistocene is represented by a series of interstratified sandstones locally called "cancagua." Outcrops of cancagua are found in both banks of Rio Calle, from where it passes through the city to where it disembogues at its mouth. Brüggen (1950) describes it in a profile made at Castillo de Niebla and maintains that it was deposited as a terrace. Sands and silts deposited by the wind overlie the cancagua. Finally, recent deposits of clays, silts, and sands are encountered in the drainage canals, valleys, and flood plains of the rivers. The cancagua and Recent deposits constitute the superficial subsoil over which the city is constructed.

Local Geology

Details of Alluvial Fill

In the present report, the Upper Pleistocene and Recent sequence is divided into six mapable units. These are presented on the geologic map. This map was made

TABLE 1

GENERALIZED GEOLOGIC SECTION OF VALDIVIA

Unit	Observations	Subject to correction	
		Maximum, cm	Minimum, cm
QV6	Recent alluvium and artificial fill, saturated; alluvium is gray to white plastic clay, black to white sands, intercalated with yellow silts and fragments of marine shells. Artificial fill, debris, and trash, such as wood, gravel, and rocks. The unit covers all the area and totally fills in the low parts	1,300	10
QV5	Recent river sand with abundant mica is encountered in topographically low areas between 1 and 2 meters above sea level.	300	100
QV4	Wind blown sand indurated with cross-stratification. It remains as remnants in the highest areas. Scant outcrops between 10 and 17 meters above sea level.	200	100
QV3	Aeolian silt, reddish-yellow, coffee-colored, abundant mica and limonite. Its upper level is between 5 and 15 meters above sea level. It forms terraces. Ten to one hundred cm coffee-colored black silt is always found above this unit.	450	30
QV2	Thick sand and gravel. Fluvioglacial, indurated, cemented with palagonite and subangular clasts of granite and metamorphic rocks. An irregularly eroded upper level between 6 and 12 meters above sea level.	700	200
QV1	Clays, sands, clayey sands, and silts of a dark-coffee to white. The clays vary from plastic to friable. They are silty; some are laminated. The sands are in general fine to medium grain, with some coarse grains. Some of these are partially indurated. One, designated QV1SS, is completely indurated and composed of fragments of volcanic rocks and granites, cemented by palagonite. Two horizons have been tentatively identified. The unit has an irregularly eroded surface from 1 to 10 meters above sea level.	600	100

from observations of exposures and hand drilled holes 2 meters in depth; units recognized at a depth of 1 meter are located on the map. Some lenticular beds do not persist across the area. With the exception of the Recent alluvium in the present drainage systems and the ancient rocks, the sediments are probably of Pleistocene age.

Unit QV1

Basically the outcrops in Valdivia are sands and clay gradationally interstratified. The generalized geology is in table 1.

The clays for the large part are plastic and silty, some of them being friable; the color of the clay, in part laminated, varies from dark-coffee to white. The sands vary from gray to coffee-colored, the size of the grains varies from fine to coarse; some beds are laminated, others show cross-stratification. One of the beds of sand is well indurated and fractures conchoidally. This bed is locally called cancagua; although it appears that this term is applied to any sand having a certain grade of hardness. This sand is finely granulated with good classification and shows no apparent structure. It is found in the greater part of the city and has been identified in the Section AA′ as QV1SS (figure 2).

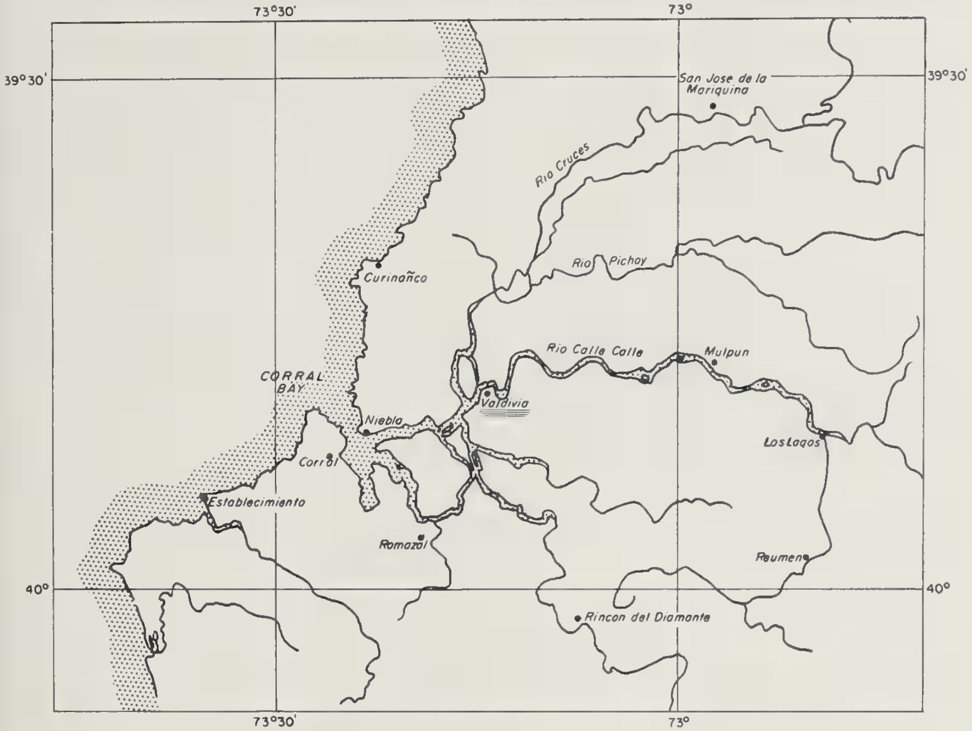

FIG. 2. Map Indicating Location of City of Valdivia.

A brief microscopic study was made of samples of the indurated sand. It is composed principally of fragments of basaltic rock, with some granite and a vitreous matrix. This indicates a volcanic origin. Muscovite is found only in very small quantities in some specimens, in spite of the fact that the predominant rocks in the outcrops of the zone are mica schists.

The rest of the beds of sand in the unit are generally thicker and of a medium- to dark-coffee color, which probably comes from a thin layer of limonite that surrounds the grains. The hardness is not homogenous, either vertically or horizontally.

In a river bank near the place that now serves as a dock is a finely stratified, sandy, gray silty clay that by its stratigraphic location probably pertains to Unit QV1. Also observed is another especially interesting clay, which appears to be a friable sandy silt of dark coffee color, but which becomes fluid when pressed between the fingers. This has been tentatively identified as halloysite. This layer may be noted in a cut at the side of the buildings of the Hoffman Industries on Isla Tejas. Stratigraphically this is, in some places, below the hard sand (QV1SS).

TABLE 2

Measured Section of QV1

Thickness, cm	Outcrop at the corner of Guillermo Frick and Clemente Escobar	Thickness, cm	Outcrop on the north side of the extreme eastern part of the bridge Pedro de Valdivia
50	Cemented sandstone. Well indurated, coffee-colored sand; medium to fine grain, interstratified (QV1SS).	50	Clay to silt, grayish, weathered, possibly old landsurface.
40	Gray limonitic sand; remains of roots.	95	Cemented sandstone, indurated, coffee-colored, medium to fine grain, interstratified; 0.5 cm of sandy silt at the base (QV1SS).
40	Fine to medium sand, lightly indurated.	80	Coffee-colored sands, fine to medium grains, interstratified, friable.
30	Coffee-colored plastic clay.	105	Silty clay, limonitized.
28	White friable clay.	16	Silty clay, limonitized.
110	Coffee colored clay with limonite.	33	Soil zone, horizontal, black.
70	Grayish sand with clay, lightly indurated.	35	Soil zone, horizon B, moldy coffee-colored sand, friable with red spots of altered material.
30	Dark-gray sand, medium to fine grain.	28	Gray plastic clays, silty, with limonite.
120	Gray sand, fine to medium limonitic, lightly indurated with some clay and concretions.		
80	Gray sand, fine to medium, some clay, fractured.		
60	Gray sand, fine, clay-like, well classified.		

At least two paleosols are distinguishable in the section. One is below the hardened sandstone (QV1SS) and the other directly above it. The lower fossil soil contains an A horizon that consists of 35 cm of graded black soil and a B horizon composed of 25 cm of reddish coffee-colored friable soil. This soil is observed in a road cut made at the side of the bridge Pedro de Valdivia and in the banks of the river.

The upper fossil soil, representing the weathered surface of the unit, was identified in the contact with an overlying layer (QV2) that consists of a zone of medium to dark coffee-colored soil in the upper part and of lighter coffee-colored soil in the lower part. The unit and the contact with QV2 is well exposed in the construction cuts of Calle Chacabuco, about two blocks from the river. The unit QV1 was exposed to erosion and weathering after its deposition, and hence presents an irregular upper surface. In general, this unit underlies the terrace in the higher area of the city and the slopes of the dissected parts. The sands and clays probably extend below all the city of Valdivia; nevertheless, an exploration will be necessary to determine the exact nature and distribution of these sediments. Information is lacking over a large part of the area as to the depth in relation to the present surface. Table 2 shows two measured sections of Unit QV1.

Unit QV2

This unit is composed of poorly classified silt, sand, and gravel, with a partially consolidated clay-like matrix. Limonite gives it a yellowish coffee-color.

The probable origin of this unit is fluvioglacial transport, because there are some lenticularly stratified beds conserved with well-rounded components. Its age is Upper Pleistocene. It extends principally from the railway station to the south part of the municipal park, with good outcrops on both sides of the low spot that crosses in the direction in the Calle Bueras; and it reaches a recognizable thickness of about 7 meters. It is not found any place north of the city terrace.

Unit QV3

This unit is a coffee-colored, clear to medium silt that is friable in places and contains enough clay to be slightly plastic. It also has some sand. The maximum thickness of the unit is 45 meters. Owing to the abundant content of mica and limonite, the silt may be derived from the decomposition of the mica schists. It does not present a stratification and is compact, even though it is not consolidated and is possibly of aeolian origin. Occasionally it is found in the walls of erosional canals, where it forms sharp scarps. This unit was apparently deposited over the eroded surface of Unit QV1 and constitutes the undissected area of the terrace. The superior part of the silt shows evidence of weathering and soil formation. It is probably post-Pliocene.

Unit QV4

This unit is composed of sands, medium to dark reddish coffee-colored, medium to fine grain, with cross-bedding, and it is lightly indurated. Its color is owing to splotches of limonite. The sands contain grains of quartz, probably of aeolian origin. The maximum thickness is measured at about 20 meters. This deposit is encountered at greater altitudes than Unit QV1 and is younger than Unit QV2.

Variations in the composition of this material from one place to another indicate that it may be representing more than one period of deposition. Few outcrops of QV4 are observed in the city and no indication exists that the sand might have been present and subsequently eroded. The recognizable outcrops are probably the remains of local deposits, possibly dunes.

Unit QV5

This unit is a sediment of clay-like sands and sands. The sand is fine to medium grained, gray, and contains abundant mica. Its origin is fluvial and represents the eroded remains of Recent current deposits.

Unit QV6

This unit is composed of Recent alluvium and artificial fill. The alluvium is located in the drainage canals, both present and old. It is principally clays and silts. The maximum thickness of the alluvium (13 meters) is encountered in the bed of the present river, as shown from soundings made when the foundations of the bridge Pedro de Valdivia were built. The artificial fill was made of a diversity of materials, all the way from sand, clay, or gravel to debris and trash utilized to fill and level low parts of the city, constituting a compact unclassified deposit. The low and even the strongly sloping areas of alluvium or artificial fill are saturated.

The unit QV6 also contains materials, deposited under Recent swampy conditions, composed of fine sands, silts, and clays, which are encountered in topographically low areas of the city.

Within the low area of the sector that extends to the west of the city, a detailed mapping was not done and everything has been included in this unit. In some places in this area there are fragments of marine shells encountered at a depth of 2 meters.

Historical Geology

The upper materials of the city of Valdivia were deposited during the Upper Pleistocene and Recent periods. The sediments that underlay Unit QV1 are probably Pleistocene and rest on the eroded surface of the metamorphic rocks, which, according to available evidence, is encountered between 125 and 150 meters below the surface or over deposits of the Navidad formation that occasionally overlies the mica schists. Logs of water wells drilled in the city indicate the presence of beds of gravel, probably fluviglacial deposits. Beds of volcanic ash have also been reported.

The basin in which the city of Valdivia is found has existed since the beginning of the Pleistocene. During successive advances and retreats of the sea it received deposits that were later eroded. In the Upper Pleistocene, sediments that in the upper part correspond to Unit QV1 were deposited below lagunal conditions, almost on the coast, forming a terrace Brüggen (1950) described as the "terrace of cancagua." Unit QV2 was probably deposited during this time. Towards the end of the Pleistocene the area was uplifted and eroded. The silts of Unit QV3 were deposited over the eroded surface of QV1, forming a terrace over the remains of which is constructed a great part of the city. Sands transported by the wind (Unit QV4) were deposited after the silts.

Subsequently, the silt was eroded as a result of the possible additional uplift, forming the present topography. The modern river bed has worked through Units QV3 and QV1. Older stream channels are found below the city and present a distinct topographic expression. A map of Valdivia made in the year 1875 shows the ancient water courses as swampy areas.

Units QV4 and QV5 were deposited since the Pleistocene. For a more complete understanding of the history, detailed study will be necessary.

Subterranean Water

The water supply of Valdivia and part of the Isla Tejas is obtained from an infiltration plant located in Llancahue, 7 km east of Valdivia, and serves 39,500

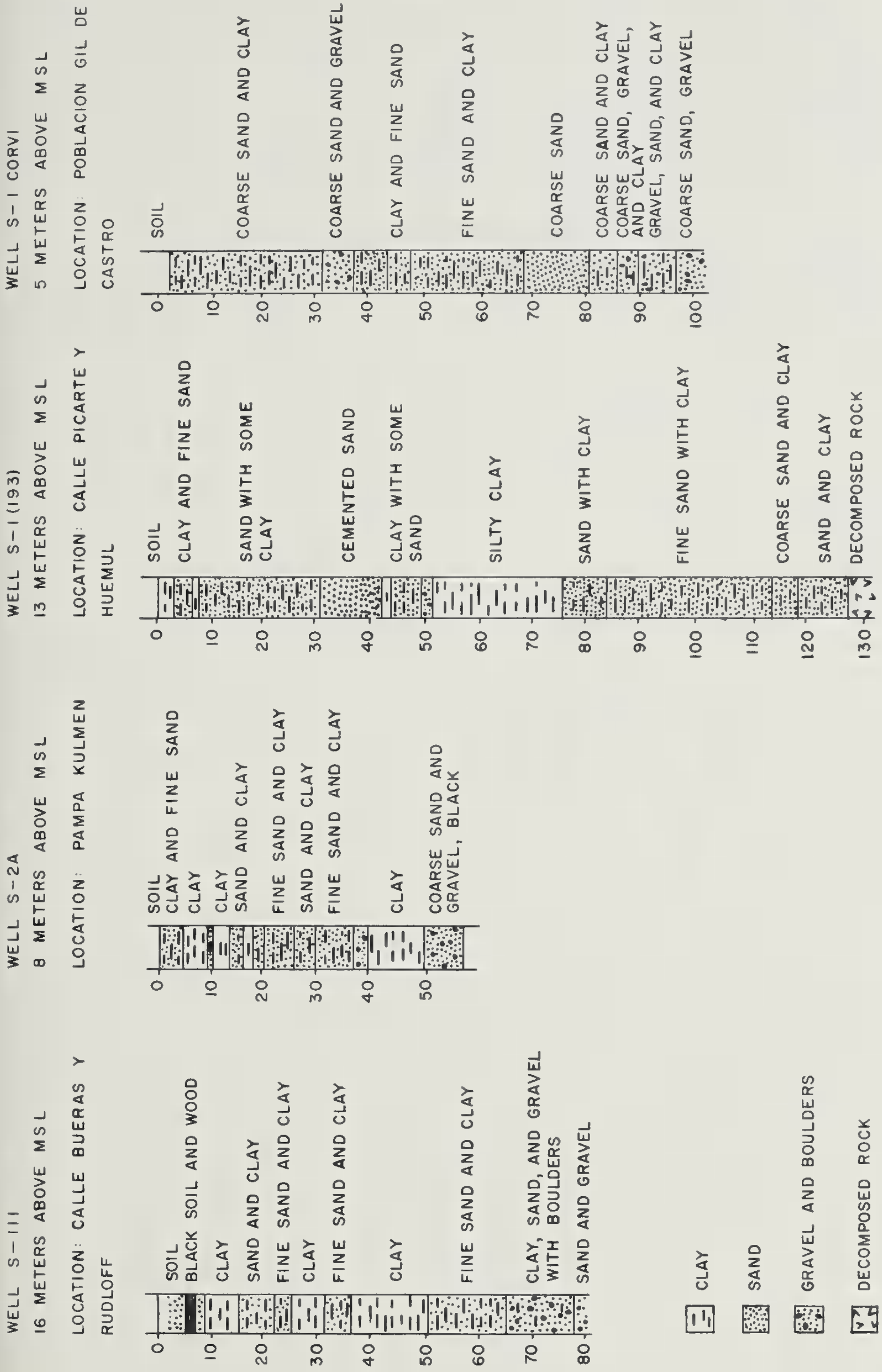

Fig. 3. Geological Data as Taken from Four Selected Wells.

people. A program of exploration for subterranean water had begun in hopes of developing a supplementary water supply.

Logs were obtained from 14 wells drilled near Valdivia that varied in depth from 42 to 131 meters. Water was found in beds of sand and gravel, at a depth of 15 to 114 meters below the surface. The water is under artesian pressure and climbs in the wells to approximately 1 to 2 meters above sea level. Two aquifers were reported in three wells perforated in the Pampa Kohlman and three aquifers were reported in a fourth well. Analysis of water from the other wells indicates that salty water exists in the deepest part of the aquifers. Data from four selected wells are shown in figure 3.

In Las Animas the water is obtained from wells drilled by hand to a depth of 1 to 2 meters below the surface. The aquifer is not artesian and is in direct hydraulic connection with the river. The wells have a low output of good quality water, each about sufficient to furnish the needs of one family.

Well logs were obtained from 17 hand-drilled wells in the city of Valdivia itself. Wells vary between 4 and 6 meters in depth and the level of the water is encountered from a few centimeters to 2 meters below the surface. Before the installation of the public water system, there had been many wells dug by hand in this city, and these were in part used during the emergency.

The unconsolidated alluvium and the artificial fill (Unit QV6) are especially saturated in the lower areas. From an outcrop of sand located at the beginning of one of the old drainage canals near the intersection of Calles, Arauco, and Pedro de Valdivia, a perennial spring flows with a discharge of $\frac{1}{2}$ meter per second. Other springs exist in and adjacent to the city, generally at the contact of one sand member of Unit QV1 with the overlying, less permeable silt member of QV3.

Characteristics of the Earthquake

The earthquake that caused the damage in Valdivia on the 22nd of May, 1960, began at 15 hours 10 minutes 47 seconds and was of magnitude $8\frac{1}{2}$. It was perceived as a continuous oscillatory movement.

The previous day there had been several earthquakes of low intensity. The number of victims in the city of Valdivia was comparatively low because it was Sunday afternoon; the weather was good and at 14 hours 55 minutes 57 seconds an earthquake of magnitude $7\frac{3}{4}$ occurred that made the people run to the streets. The earthquake was followed by a tidal wave that caused damage along the coast and whose effects were propagated into Valdivia, producing an inundation of low areas. The wave reached an altitude of about 1 meter on the banks of Rio Calle Calle in front of the city.

Verbal information in Valdivia indicates that the earthquake had a slow undulatory movement; there was no unanimous accord as to its direction. Between the 21st and 22nd of May there had been numerous aftershocks of the earthquake at Concepción. After the 22nd of May, aftershocks occurred with epicenters spread between Concepción and Aysén.

Geological Manifestations of the Earthquake

Sinking of Land

No evidence exists for displacements by faulting in the region of Valdivia; nevertheless, the earthquake produced some changes in the topography. Actually, a great area in the Valdivia region has submerged, and it has been suggested that this forms a part of the general settlement of the coast. In the area studied, the greatest part of the sinking is probably caused by compaction of saturated, unconsolidated alluvium. Before the earthquake, many areas were no more than 1 or 2 meters above the reach of the tides. The movement of the earth occasioned by the earthquake compacted the saturated sediments, expelling the water therefrom, which permitted an additional compaction. The majority of these terranes, which cover large areas in the river valleys, probably will remain submerged.

Various areas that were submerged after the earthquake are re-emerging slowly. The submergence was probably due to one or two reasons, or a combination of both. The water of the seismic sea wave penetrated depressed areas, remaining there after the retirement of the wave. The level of the water could have been subsequently lowered by evaporation, infiltration, or superficial runoff. For the moment, such areas are exposed to the inundations during periods of strong rains.

Slumping

It has been mentioned that the Recent alluvium and the artificial fill were not compacted and contained a great quantity of water. The earthquake produced slumps in a great part of these terranes, especially in those that were under pressure or that were not supported on one or more sides. Along the banks of the Rio Calle Calle, the fill slid towards the river, destroying a great part of the Avenida Pratt and affecting buildings and port works. In areas where artificial fill was used to construct streets across low places, these slumped, causing displacement of the blocks of pavement. The filled low spots had open lurch cracks in them that bespeak the great intensity of the movement at these points.

Landslides

Apart from the slumping previously mentioned, landslides were not observed within the city. These were noted outside of Valdivia, principally in road cuts and on river banks.

DAMAGE FROM THE EARTHQUAKE TO THE STRUCTURES CONSTRUCTED BY MAN

In Valdivia a study was made of the damage to man-made structures occasioned by the earthquake, so that the relation between the geology and the damage could be determined. The study consisted in making traverses along selected streets, noting the type of construction and damage to each building on one side of the street. Figure 4 shows the lines of the traverses. The classification used for the structures includes five types of construction:

1. Reinforcement with steel and construction with reinforced concrete
2. Masonry and brick work
3. Wood frame
4. Foundations of reinforced cement and the upper parts of brick or wood
5. Wood frame covered with brick or concrete

There were eight types of damage noted: complete destruction, walls destroyed, fall of roof, fractures, fractured without possibility of repair, fallen wall, inclined wall or house, and failure of the foundations. When more than one type of damage was observed in a structure, only the principal one was noted. For example, if a wall failed as well as a roof, the fall of the wall was noted, since the fall of the roof could have been produced later; or if a house had totally slid off its foundations and was found inclined, the failure of the foundation would have been noted as the principal damage.

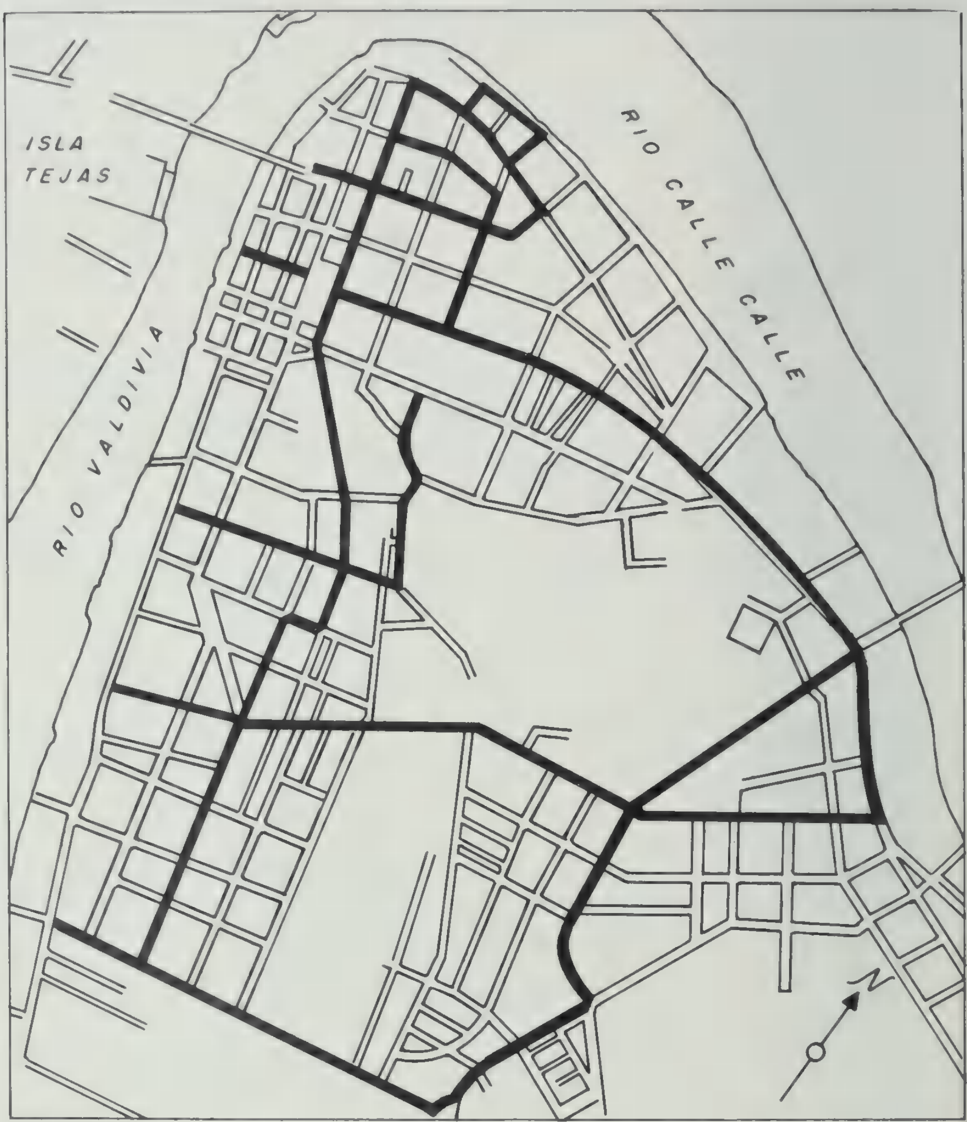

FIG. 4. Traverses Followed during Reconnaissance of Damage of Cultural Developments.

The study was neither complete nor detailed. Of the houses observed, 53 % suffered some damage by the earthquake. No traverses were made in undamaged areas, so the general percentage of damage was probably less. Figure 4 shows new undamaged construction. The greatest destruction was produced in the part of Valdivia limited on the north and on the west by Rio Calle Calle and on the east and south by Avenida Bueras and along both margins of the river. The greatest damage was concentrated in lower parts of the area.

The results of the study of the damage are shown graphically in figure 5. Many

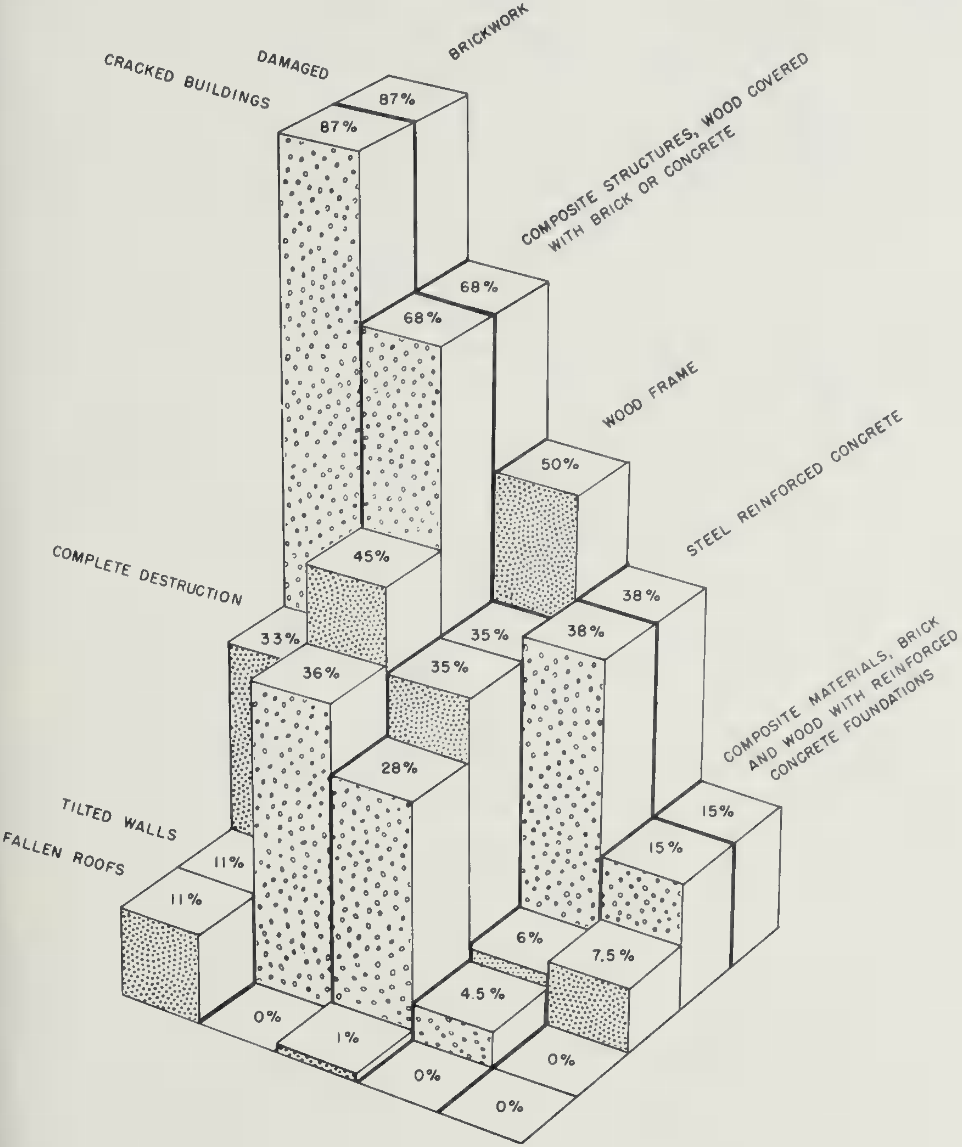

FIG. 5. Graphic Illustration of the Results of the Study of Damages.

structures of wood were damaged because the houses were constructed on inadequate foundations or were not fastened to them. Some houses simply slid off their foundations, others were located on posts and the movement of the earthquake made them fall.

The fall of fire walls, many of which were brick, often damaged the adjacent structures. Brick coverings over houses of wood fell, often without causing any other damage to the remaining structure. Brick structures of all types suffered the major percentage of damage.

Edifices with lower floors of reinforced concrete and upper floors of wood apparently suffered less damage than any other type of building.

The two bridges of the Rio Calle Calle were damaged, even though both remained in service. The central pillars, seated at a greater depth, apparently remained firm while the pillars on the extremities moved.

Many streets were damaged. The pavement broke and the plates of concrete were inclined as a result of the compaction of underlying sediments. Avenida Pratt, the waterfront street of Valdivia, was almost completely submerged. Drains and water pipes were broken in areas of artificial fill. Many retaining walls, the majority of which were constructed without supports, fell, permitting the slumping of the materials that they were sustaining. Many gravestones fell without any particular orientation. Many of the mausoleums constructed of brick in the old cemetery in the municipal park were in part destroyed. Two statues in the principal plaza fell, one toward the other, one with a rotary movement and the other without.

Relation Between Damage and Geology

The results of the study of the damage indicate that the areas with the greatest damage are those areas with outcrops of Unit QV6 — recent alluvium and artificial fill. The unconsolidated and saturated deposits of Unit QV6 transmitted more movement than the more compact members of the geologic units, resulting thus in more damage to the buildings and the streets on outcrops of QV6 than to equivalent structures on the outcrops of the other units.

The nature of the damage on the other geologic units has indicated that the damage was more a function of the construction than the movement of the land. Comments of the engineers, Steinbrugge and Clough, who visited the city indicate that with comparatively slight changes in the method of construction, the damage would have been much less or of scant importance.

The damage on both sides of Rio Calle Calle was caused by the failure of alluvium and of artificial fill (QV6) that lined the two banks. The older units that form the scarps remained firm. The inundated parts of the city and the surrounding areas are all underlain by Unit QV6. The damage, including slumping and inundation in areas of QV6, was clearly caused by the reaction of these sediments to the earthquake. The lack of similar evidence in the outcrop area of the other units underlines the difference in the intensity of movement between the older sediments and those of unit QV6.

Resumé and Recommendations

The information contained herein represents only a brief reconnaissance of the area of Valdivia, so this report should not be considered as definite. Nevertheless, we can give some conclusions. Probably because of the Recent alluvium (QV6), lower places along the river are submerged, many of which remain thus. Several terranes in the city have suffered a similar compaction and will be inundated after strong rains, if an adequate drainage is not developed. Any construction in the areas of outcrops of Unit QV6 will necessitate special study of the soil to predetermine its design. To corroborate this fact, reference is here made to a report on soil mechanics of the "Poblacion Valdivia," made by the Instituto de Investigaciones y Ensayes de Materiales (IDIEM) at the request of the builders and signed by engineer Francisco Dick. This report, Test Certificate No. 48,401, 6 January 1959, clearly shows the land to have, for the more compact horizons, a bearing strength of about 1.7 to 2.0 kg/cm^2. The report recommends methods of preparation that were followed with evident success. Said "poblacion" was constructed in part over a garbage dump filled with adequate material, following the specifications of IDIEM, and did not suffer damage. This does not signify that the area of Unit QV6 can be reconstituted; studies should be made in each case.

ACKNOWLEDGMENT

The authors would like to thank the functionaries of the municipality of Valdivia, especially of the Department of Architecture, and architect Sr. Brieva of the Department of Planification and Ministry of Public Works, for facilitating maps and information about damage, as well as engineer Sr. Frederick Wiese, who gave the authors the data obtained during the construction of the Pedro de Valdivia bridge. Srs. Ernest Dobrovolny and Richard Lempke of the Engineering Geology branch of the Geological Survey gave active cooperation and advice and were a great help in preparation of the present report. Finally, we would like to acknowledge the collaboration of all the residents of Valdivia who aided in the investigation and thank them for their good will and enthusiasm in answering questions and giving the authors access to their property.

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GEOLOGIC REPORT ON THE EFFECTS OF THE EARTHQUAKE OF 22 MAY 1960 IN THE CITY OF PUERTO VARAS

By Herbert Thomas, William Bowes, and Nelson Bravo S.

(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

Damage in Puerto Varas was largely confined to the low, central part of the town, to the steeper slopes, and to the edges of terraces. The topography and geology are discussed and recommendations made as to steps to be taken to prevent future damage.

Introduction

In June 1960, the Institute of Geologic Investigations, Chile, sent the authors to study the effects of the Chilean earthquake of 22 May 1960 in Puerto Varas (figure 1)and to delineate dangerous zones and favorable zones for reconstruction. A map of Puerto Varas without elevations or contour lines was used as a basis for figure 2 (in the pocket at the back of this number). Conditions in Puerto Varas were studied during the morning of 29 June 1960.

Topography

The city of Puerto Varas is located around the southernmost bay of Lake Llanquihue; the center of the city lies on the waterfront of a secondary bay called Puerto Grande. The landscape consists of an undulating high terrace that forms a steep bank near the edge of the lake. The plaza and business district are situated in the center of a low, flat zone 2 or 3 meters above lake level. Several creeks that come together in this area from the east and the north have deeply incised the high terrace that surrounds the city. To the north of this basin, part of the city, including the railroad station and the Grand Hotel Puerto Varas, is constructed upon the intermediate terrace. North of the station the city terminates on an even higher terrace. Toward the south and the east-southeast, the intermediate terrace extends over a greater distance; a large part of the city lies on this plain. To the west and the south, outside the urban area, a still higher zone of elongated ridges composed of eroded remnants of terminal moraines is found.

Geology

All the terraces in the vicinity are composed of a thick, dark gray, clayey fluvioglacial sand that is stratified and partially cross-bedded. Lines of boulders form conglomeratic beds 1 or 2 meters thick in places. Remnants of terminal moraines are easily recognizable on the surface of this terrain as ridges of till containing large subrounded blocks. The boulders in this unselected and unsorted material are large and small, rounded and angular, fresh and weathered almost to disintegration, and of both igneous and sedimentary nature. According to Brüggen (1950), these ridges are the last remnants of postglacial terminal moraines.

At about the level of the lake in the bay of Puerto Chico beneath fluvioglacial terrace material, delicately folded and bent beds of a gray lacustrian clay crop out.

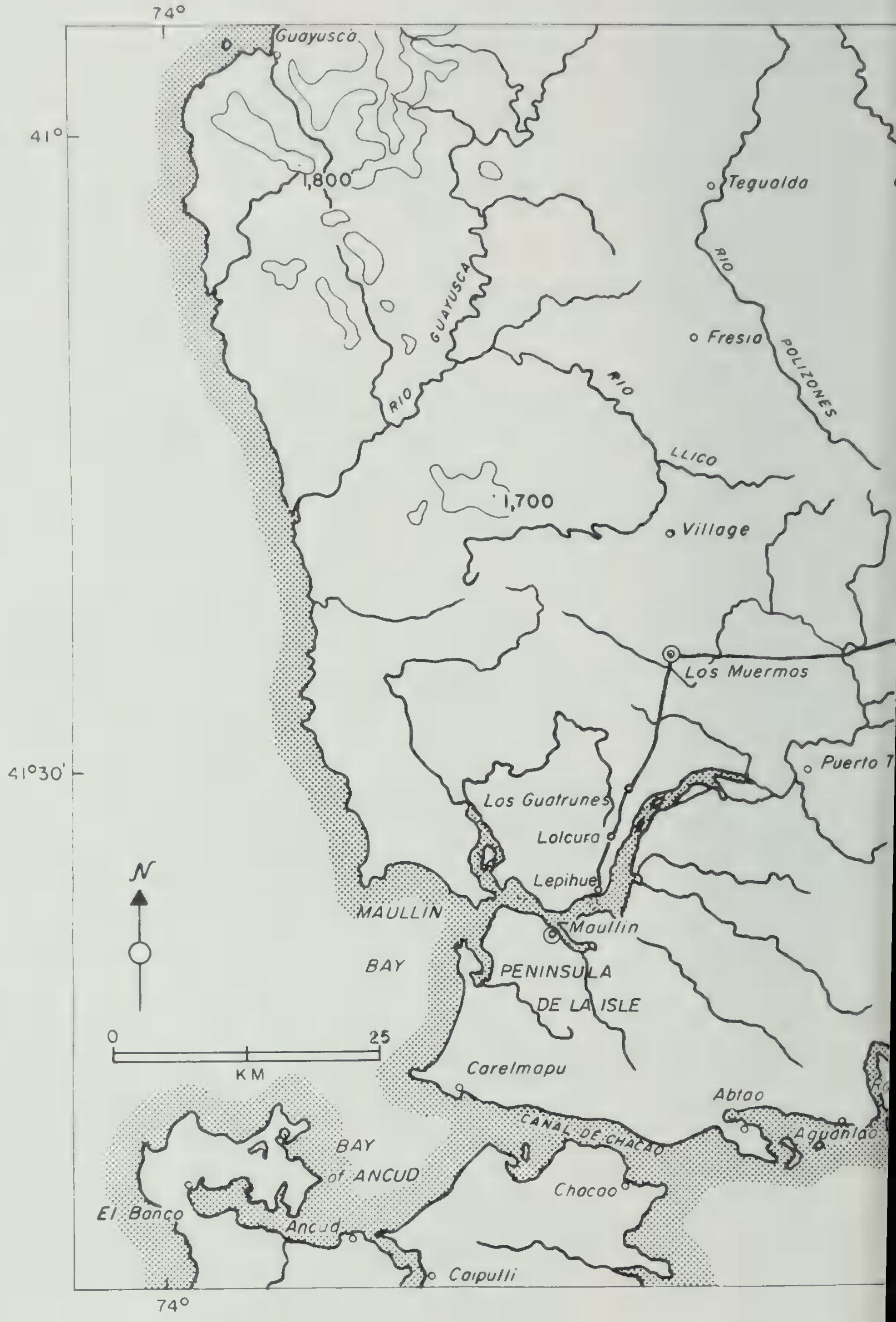
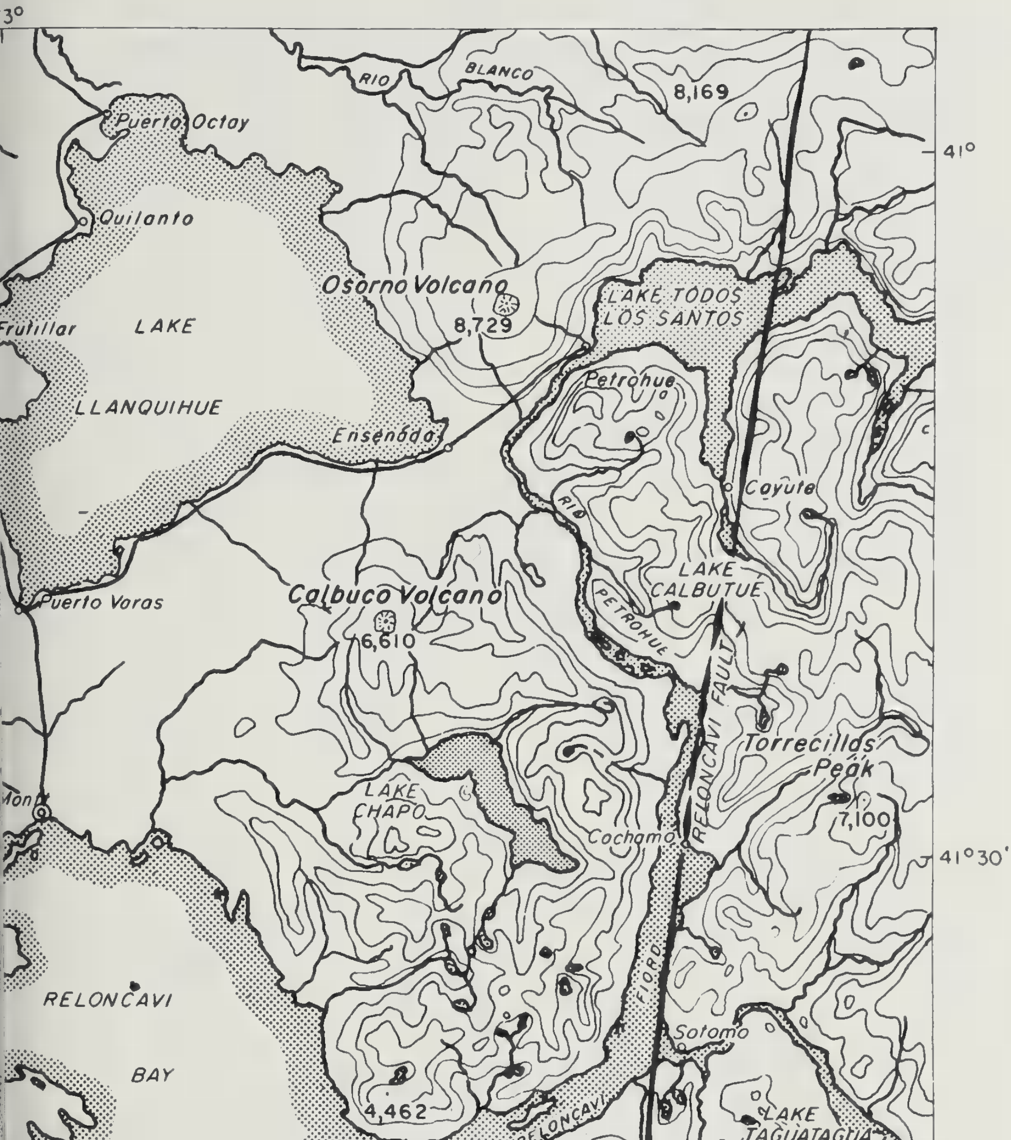


Fig. 1. Regional Ma


3°
RIO
BLANCO
8,169
41°
Puerto Octay
Quilanto
Osorno Volcano
8,729
LAKE TODOS LOS SANTOS
Frutillar
LAKE
LLANQUIHUE
Petrohue
Ensenada
Cayute
RIO
PETROHUE
LAKE CALBUTUE
Puerto Varas
Calbuco Volcano
6,610
RELONCAVI FAULT
Torrecillas Peak
7,100
Mont
LAKE CHAPO
Cochamo
41°30'
FIORD
RELONCAVI
BAY
Sotomo
4,462
RELONCAVI
LAKE TAGUATAGUA
7,169
Aulen
Hornopiren Volcano
7°

uerto Varas.

When the glacier crossed the lake, deepening it in the center and folding and bending the sediments at the edges, it mixed a bit of the deformed mass with the basal moraine. Later, during and after the retreat of the glacier, fluvioglacial material was deposited on top of these beds of tight and well compacted clay.

The creeks that meet in the low zones in the center of the city have cut deep channels in the different terraces. Material carried away by the creek waters has been redeposited as an alluvion (mudflow) in the bottom of the canyons and in the level city center on the bay of Puerto Grande. The continuation of the alluvion in the water probably forms a small deltaic cone of soft sand and boulders.

Description and Interpretation of the Effects of the Earthquake

In Puerto Varas the damage caused by the earthquake was small in comparison with the destruction in other cities. This is because the soil is better compacted on the intermediate and high terraces. A few landslides were observed in the high zone and in road cuts. The smooth slopes of the moraines were cracked.

In the high part of the city north of the central zone, buildings of concrete and stone, such as the Grand Hotel Puerto Varas and the railway station, were only slightly damaged. The hotel has some cracks in the walls and in one place the floor settled a little. In the hotel terrace, a few pillars of the arbors are a little out of plumb. The well built chalets near the hotel show no signs of damage. One of the concrete water tanks near the railway is damaged and out of use. The houses to the north are principally of wood and these were not damaged by the earthquake. At one place in the intermediate terrace there is a large, wooden house of six or seven floors, apparently intact, demonstrating the superiority of wooden construction built to resist oscillatory movement.

On the terraces south of the center of the city, in the zone where the public schools, the convent, and the church are located, there was very little damage, but the Chapel of the Nuns at the side of the intact convent building is completely out of plumb.

The authors did not have the opportunity to examine the material of this church, but it appeared to be of poor quality, since it was damaged despite its location on ground that did not seem dangerous. The large wooden church, which was undergoing construction, did not suffer any notable damage, in spite of its position near the edge of a canyon full of cracks. However, directly east of the church, farther from the quebrada (ravine), a several-story house constructed of a mixture of wood, concrete, plaster, bricks, and iron was half destroyed. The mixture of elastic materials, such as wood, with breakable and rigid materials was responsible for the damage.

In the little park to the north of the church, half-way down the slope that descends to the bottom of the canyon, is the Grotto of Lourdes. Here all the trees, even the little ones, fell to the soil. The trails and banks of rock slid down. The statue of the Madonna of the Grotto also fell, but was undamaged. This park is located on a soft humus soil composed, very probably, of artificial fill and material from an ancient landslide: the worst possible materials that could be found. The tremendous quantity of parallel compaction cracks in the little park and at its side demonstrate clearly that the shaking made the soil slide down and settle.

To the west of the railroad, on the same terrace, rises an isolated hill, Monte Calvario, located on fluvioglacial material. Large blocks crop out, indicating that the top of the hill is the remains of a moraine. The statues of the Saints on the summit fell to the ground. The bas-reliefs of the 14 stations of the Road to the Cross, which are situated along the trail, show damage that gradually lessens from the top to the bottom. The top of the hill, being without lateral support, reacted to the shakings of the earthquake with movements of greater amplitude.

On the terrace east-southeast of the central zone, between the shore and the railway, the houses are almost entirely of wood and were not seriously damaged. Along the lake, cracks and landslides are found in the cliff that forms the limit of this terrace. In the park in front of Puerto Chico the concrete road that continues to the east around the lake (not shown in figure 2) and the old road to Puerto Montt were seriously disrupted. As the cliff in the high part is practically vertical and consists of a bed of sand that was saturated with water at the time of the authors' visit, it was recommended that the growth of the cracks be watched and perhaps the central part of the road by the lakeside be closed. The houses along the road at the lakeside do not show much damage, which indicates that the terrace is fundamentally sound. Behind the houses the slope climbs smoothly to the more or less plane surface of the terrace. As in Llanquihue, there were accumulations of water formed large swamps in several places on the safe terrace. The week in which the area was visited there were heavy rains and it was difficult to decide whether these swampy spots were due to the excess water or if they are of a permanent character. In any case, drainage was recommended before constructing houses in these areas. These may be the gravelly remains of ancient creeks or artificial fill accumulated there to fill in a small local depression and level the terrain for future construction of streets or houses.

Truly dangerous zones for construction are found on the edge of the steep slopes, in the slopes themselves, and often in the bottoms of the quebradas. The effects of the earthquake are well displayed where the railroad crosses the big quebrada west of the central part, and in the quebrada to the south of the central zone, clearly showing the danger encountered in building in such places. In the center itself, where the quebradas come together, notable damage was ovserved in the pavement of Salvador Street. Cracking and slumping were noted also to the west on Calle San Bernardo and to the north on Calle Portales. Near the shore, Hotel Playa lost one of its lateral walls. Landslides occur along the coastal road, and the two docks are somewhat out of level. It is evident that the center of the city was constructed over very soft soil; i.e., alluvial material from the quebradas. This mudflow material is composed of poorly compacted muddy sands and loose gravels that extend below the waters of the lake. The pillars of the docks are founded in part on this cone of loose sediments.

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FIELD OBSERVATIONS MADE BETWEEN PUERTO MONTT AND MAULLIN

By Herbert Thomas, William Bowes, and Nelson Bravo S.
(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

The effects of the earthquakes between Puerto Montt and Maullin were lurches in soft material and a possible fault movement just east of Los Muermos.

Pine forests were killed by submergence of the land and the city of Maullin has descended at least 1.5 meters and several of the streets are now inundated.

Introduction

During the period of study of the Pto. Montt region, a one-day excursion was made to Maullin to observe the effects of the earthquake in that town and en route. The location of Maullin is shown in figure 1 of the paper by the same authors on Puerto Varas, starting on page 1347 of this number.

Pto. Montt to Lolcura

The road between Pto. Montt, Las Quemas, and Los Muermos is situated principally upon a gently undulating plain of low relief that coincides with the level of the highest terrace near Pto. Montt. The plain is in places dissected by deep valleys and modulated by old outwash channels and wide valleys of 2 or 3 meters depth formed by the meanderings of the channels of secondary streams. The terrain is composed of fluvioglacial sediments essentially identical to those observed in and around Pto. Montt: silts, gray sands, and intercalated boulder horizons of no great extent. The material is stratified and in places cross bedded. In places, long ridges are superimposed on the surface of the terraces. These ridges show no bedding, contain subangular boulders, and appear to be remnants of terminal moraines.

The new airfield of Pto. Montt, Tepual, situated on this surface, was not affected by the earthquake. The runway is well made, the sediments underlying it are well compacted, and the site is far from any steep slope.

The isolated houses in the countryside were damaged but little. Some barns collapsed because of an excessive interior load of heavy sacks or of grain that moved with the earthquake, overthrowing the walls. Small cracks and landslides could be seen in road cuts and on the sides of deeper valleys.

Just east of Los Muermos, at the end of the railway station, cracks in the slopes were more notable. Sr. L. Aguirre Lebert of the Instituto de Investigaciones Geologicas and James M. Jordan of the United States Coast and Geodetic Survey flew over this region and reported that the cracks seemed to lie more or less parallel and in a north-south zone, indicating a fault of some consequence (Jordan, 1961). This is an interesting observation, and these cracks may truly represent a fault. The locality is a likely one, presenting as it does a line of change in the topography. Our own observations, however, lead us to believe that these are all lurch or compaction cracks formed by settling of superficial soft material and humus. As of this writing, no certain indication of fault movement has been found between

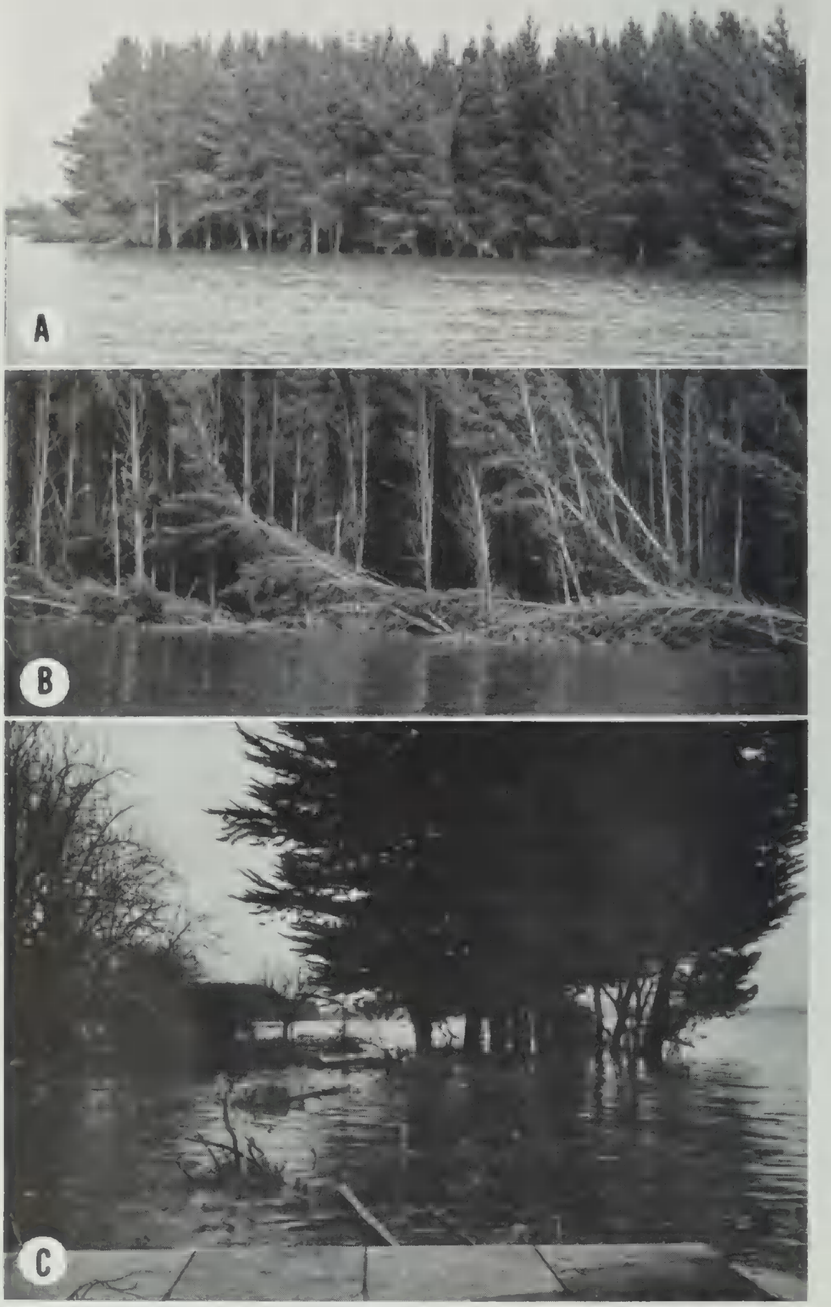

FIG. 2. Effects of Inundation in a Pine Plantation to the East of Maullin. In figure 2 c part of a former street is visible. Photos by H. A. Grosse, Pto. Aisen, Chile.

Puerto Montt and Maullin. It has been proposed that the Instituto Geografico Militar will re-level the region. When the new results are compared with those of previous levelings, a change may be noted.

The concrete houses of the Southern Dairy, located near a creek east of Los Muermos, were partially destroyed or cut by cracks. A concrete water tank east of Los Muermos was slightly cracked, although the concrete office building of the water company was undamaged.

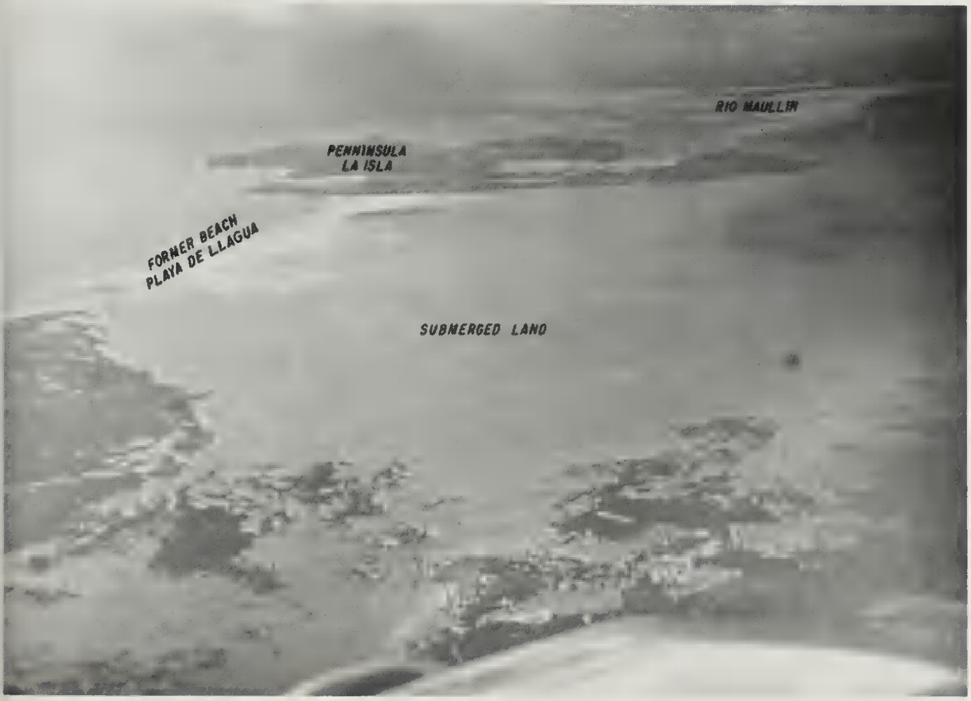

FIG. 3. Submergence of Farm Land Near Coast. The Golfo de los Coronados is to the upper left, Maullin on the extreme upper right. The breaker zone represents the former Playa de Llagua, and the island was formerly Peninsula La Isla. The area of shallow water in the center was pasture and farm land. Photo by Pierre St.-Amand.

REGION OF MAULLIN

The road beyond Lolcura, flooded and in part destroyed by the tidal wave, was intransible at the time of our visit. At this point, the Rio Maullin is crossed by a little motor-launch. The river was very wide here; all the bank was sunk and inundated. Isolated trees, far from the present bank, gave an idea of the extension of land, now submerged, that was formerly dry and cultivated. Along the northern side (of the river) were seen isolated houses with their foundations at and in the water. Figure 1 (in the pocket at the back of this issue) shows a sketch map of Maullin.

The southern bank appeared to be composed of a slightly higher terrace, but the houses at the foot of this terrace were very nearly at water level.

Sr. Augusto Grosse of the Aysen department of roads, who was charged with taking photographs of all the area affected by the earthquake, showed us photographs taken of some pine plantations to the east of Maullin (figure 2). In these photographs, taken before our visit, the plantings are in the water. The main part of the plantation is brown and dead, and only the trees in the areas not reached by the wave are still green. According to Grosse, the trees having their roots in the sea water were dying. The part of Maullin constructed over the low terrace already mentioned was almost undamaged and was not reached by the water. In the photographs of Grosse, the water has a higher height than during our stay. There is no doubt that all of the region of Maullin had sunk, but there appears to have been a slight emergence since. According to an engineer from Puerto Montt, the sinking was at least 1.5 to 1.8 meters. In consequence, Peninsula de la Isla, the peninsula to the southwest of Maullin, had lost its connection with the continent and had transformed itself into an island (figure 3).

The earthquake itself, according to a verbal report of an employee of "Obras Publicas," was not intense in Maullin.[1] The tidal waves that came later, however, reached the pine plantations and arrived at the Plaza of Maullin where there was considerable damage. Various houses on the bank were destroyed and carried away by the water. Figure 1 shows the state of the town after the tidal waves. An old ferry boat, a vessel of some 15 meters length, was carried out of the water by the tsunami and is now high and dry about ½ kilometer inland.

In resume, it may be said that the sinking of all of this region is a geologic fact caused by tectonic movement. Up to now, it has not been shown if this is only a light inclination of the coastal zone that gradually decreases to the interior, or if it represents a homogenous sinking of all of a great block. This problem will probably be resolved by the new leveling projected by the Instituto Geografico Militar. The science of earthquakes is not sufficiently advanced to make predictions with respect to the occurrences and probable force of future earthquakes. Nevertheless, it can be said, with security, that if the tectonic movement of ground sinking is going to continue with future earthquakes, the only recommendation that may be made for protection against tsunamis and inundation is to construct on the higher parts of the shores.

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[1] Translator's note: This observation may not be too typical. R. Garcia S. of Maullin, interrogated by the translator, said that the earthquake lasted 3 to 5 minutes, that he fell to the ground, that dishes and furniture fell, and that some good frame houses were put out of plumb but that none fell from the effects of the earthquake alone. My estimate was MM Intensity VII + VIII.

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GEOLOGIC REPORT ON THE EFFECTS OF THE EARTHQUAKE OF 22 MAY 1960 ON THE CITY LLANQUIHUE

By Herbert Thomas, William Bowes, and Nelson Bravo S.

(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

Damage occurred from landsliding and mass movement on the steep slopes of terraces and from subsidence and inundation in the swampy central zone of Llanquihue. Large structures located on well-drained terraces were undamaged. The glacial history of Lake Llanquihue is discussed.

Introduction

In June 1960 the Instituto de Investigaciones Geológicas sent the authors to Puerto Montt to study the effects of the earthquake and to determine the suitability of various areas for reconstruction. While in Puerto Montt, the group was asked by Sr. Ventura Gonzalez, architect of the Direccion de Planeamiento, to study Puerto Varas, Llanquihue, and Puerto Montt. See figure 1 of the paper by the same authors on Puerto Varas, starting on page 1352 of this number. This study began on 29 June, with subsequent visits to Llanquihue. A map of Llanquihue, made in 1952 by the Servicio National de Estadistica y Censos, was used to prepare figure 1 (in the pocket at the back of this issue).

Topography

The city of Llanquihue is situated on the southwest bank of Lago Llanquihue, directly to the north of the point where the lake is drained by Rio Maullin. Terraces a few meters high line the coast on both sides of the outlet. The terrace to the south of Rio Maullin is the highest, reaching a height of 12 to 15 meters. A short distance inland, north of the river and west of the terrace along the shore, is a basin that drains southward into the river. The wide part of this basin is very swampy and contains small lakes whose form and size depend upon the water level. Behind this basin is a high ridge that forms the edge of an extensive terrace. Rio Maullin cuts into this ridge a deep and narrow canyon.

Geology

The surface of Lago Llanquihue is 31 meters above sea level; the lake is more than 350 meters deep. The lake was formed, or at least deepened, by a gigantic glacier that flowed out of the mountains during the Glacial Epoch. Later, during the withdrawal of the ice, terminal moraines were deposited; today these have been extensively removed by alluvial erosion. The ridge mentioned in the preceding paragraph is formed partly of morainic material, as is indicated by large boulders cropping out at several places in the highest part.

The terraces at the edge of the lake are composed of fluvioglacial material: a fresh, dark gray sand that is in part coarsely granular and in part fine and clayey. The material is stratified, in places cross-bedded, and displays occasional lines or beds of boulders. In certain localities, a bed of fine sand 5 centimeters thick, mixed with volcanic ash, serves as a guide horizon. A bed of very fine, light gray, indurated clayey sand crops out at lake level near the housing area of the INSA beet sugar plant. Mr. E. Dobrovolny of the U. S. Geological Survey identified this as an older Lacustrian deposit over which the glacier pushed its basal moraine.

On both sides of the outlet and in the swampy basin to the north of Rio Maullin is a terrane of poorly consolidated deltaic sediments formed at a time when the river drained into the lake instead of the ocean.

Brüggen (1950) has proposed that during part of the past glacial period Lago Llanquihue, together with Rio Petrohue, drained through the Reloncavi Valley to the Estero de Reloncavi (see fig. 1). Later, following activity of the volcanoes Osorno and Calbuco (fig. 1), the connection with Rio Petrohue was cut off and the lake level rose, once again permitting Rio Maullin to drain the lake.

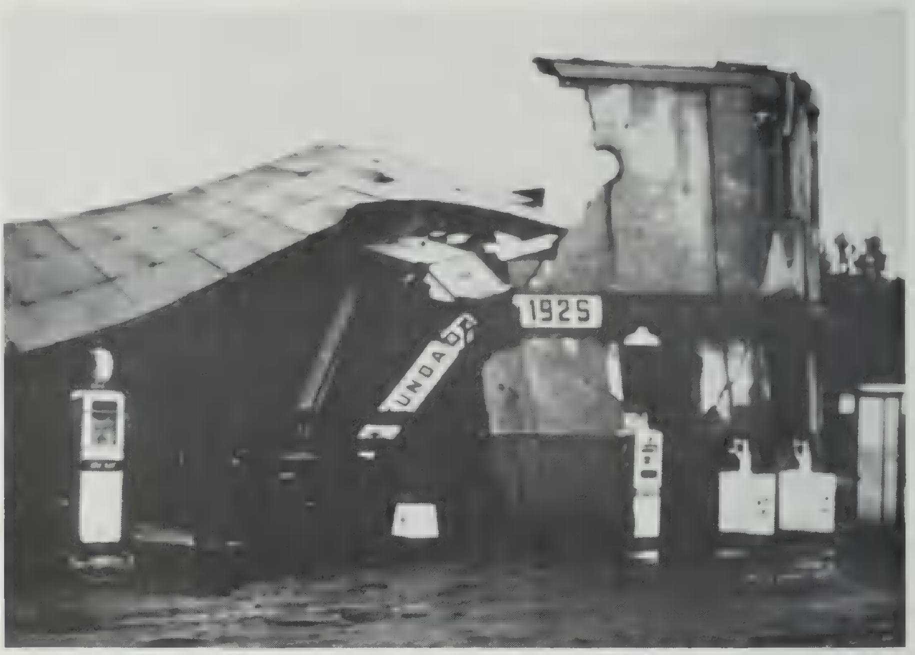

FIG. 2. Damage to Concrete Garage on Calle Baquedano.

The deltaic sediments of the basin were thus never consolidated by glacial action or overlying sediments. They are very porous, can absorb large quantities of water, and contain organic material.

DAMAGE TO LLANQUIHUE

Most of the damage occurred in the swampy basin, where the earthquake brought about a compaction of the sediments that inundated a large zone. Most of the houses have sunk into the ground, in some cases several decimeters. Some have fallen or are completely out of plumb and others have turned over or slid downhill. Near the lake, a number of houses are half flooded.

The landslides and sinking are the result of the settling of this poorly consolidated sediment. The vibrations of the earthquake expelled water from the sands, and the porosity and the volume of the sediments were reduced.

North of the road to the Corvi housing area the swampy zone is narrower and the damage less. Many houses on slightly higher ground show only little external damage. Nevertheless, the concrete garage of the Esso Corporation on Calle Baquedano almost completely collapsed (fig. 2). The buildings of the railway station have good foundations and are almost intact, but the railway itself, especially to the south, has slid a great deal. On the terrain to the east of the station, the damage is less and is of irregular distribution. This damage is probably because of small swampy zones of sand and loose gravel. In some cases, these were the result of changes in minor stream channels made by the colonists, or artificial fill used to level the ground.

The level of the lake has not risen, as may be seen near the government dock or in other places.

In the zone between the Plaza and the railway bridge, damage was considerable and the soil was cracked. This is the region of present-day drainage, with saturated sediments. Subaquatic landslides occurred. Sinking and destruction, especially of heavy concrete structures, was general. Compaction of the soil resulted in a general inundation. A tongue of sand northeast of the bridge, shown in figure 1, has disappeared, indicating a local settling. William Bowes observed several subaquatic landslides near the former location of this tongue of sand while flying over the lake. The railroad bridge has settled a little; according to Engineer Meyer, the greatest settling is in the center. Small areas of the south bank are inundated.

A short distance south of the bridge rises an extensive terrace, upon which are found the dairy Lechera del Sur and the sugar factory INSA.

This terrace, some 10 meters in height, is composed of fluvioglacial material consisting of stratified clayey sands with a few beds of boulders. This material rests upon well-consolidated beds of sandy clay with boulders derived from the basal moraine, compressed, in years gone by, by the weight of a tremendous glacier until it became indurated to the point of resisting the blow of a geologic hammer.

The tall recently constructed concrete buildings are not damaged. In spite of the fact that the houses in the housing area of the sugar factory are constructed of wood they all had concrete firewalls, and escaped damage. Usually the poorly supported firewalls break off and fall against the houses, knocking them over or out of plumb. The intact condition of the firewalls is the best proof of the stability of this terrane.

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EFFECTS OF THE EARTHQUAKES OF MAY 1960 AND GEOLOGIC RELATIONS IN RIO NEGRO

By Herbert Thomas, William Bowes, Nelson Bravo S., and Aldo Moraga
(Translated and abridged by Pierre Saint-Amand)

ABSTRACT

Damage to the town of Rio Negro was extensive along a long thin ridge lying between Rio Forrahue and Rio Llay-Llay and on the adjacent banks. The damage was largely produced by mass movement, although the actual oscillatory ground movement may have been greater on the higher parts of the ridge. A possible north-south fault is indicated. The subsoil is glaciofluvial sands and gravels. Recommendations for reconstruction are given.

Introduction

The city of Rio Negro (figure 1), located 26 km south of Osorno, was visited by the first three authors on 1 July 1960 and later by Thomas and Moraga. The town was studied to determine the relation between earthquake damage and surficial geology and to advise on sites for reconstruction.

Topography: Rio Negro is situated at the confluence of the Rivers Forrahue and Llay-Llay (figures 2 and 3; the latter appears separately as an insert at the back). The center of the city is located on a long narrow ridge between the rivers; the suburbs extend to the valleys and up the slopes to the terraces on either side. The rivers are incised in the general plain of the central valley. The highest part of the ridge is flat and is probably a part of the general surface of the central valley. On the sides of the river valleys ill-defined benches may be observed. These are probably the remains of river terraces or perhaps, in some cases, old landslides.

Geology: Rio Negro is situated on the fluvioglacial and alluvial fill of the central valley. Glacial moraines are not found in the immediate area. Only fluvioglacial sediments are exposed in the river banks. They are composed of poorly stratified sands with variable amounts of clay and occasional lines of cobbles that in places become true beds of conglomerates. Banded clays of lacustrian origin are not seen. The southernmost parts of the Province of Llanquihue reveal clean, fresh, dark gray clays, sands, and conglomerates; but all the sediments and conglomerates of Rio Negro are deeply weathered, possibly before implacement, are of an orange or coffee color, and contain humus. They do not seem to have been deposited in a lacustrian environment but at some distance from the lakes and glaciers, nor are they as well-compacted as the fluvioglacial deposits in the lake region.

Along the road between Rio Negro and Osorno a considerable extent of the fine-to-medium, poorly classified gray sandstone, locally called concagua, forms an almost flat surface. This rock is horizontally stratified, although in places the stratification is poorly visible. This was probably deposited in calm water. These rocks are fresh in appearance and were deposited without notable weathering. Occasional weathered boulders, possibly ice rafted, are found in the concagua. The concagua is surprisingly well compacted for a quaternary sediment and has proved to be good foundation material in Osorno.

Nearer to Rio Negro, the concagua is absent, possibly having been removed by erosion and redeposited as cross-bedded fluvial and torrential deposits in the prehistoric valley of Rio Chufin from the present Rio Chufin to Rio Forrahue. Thick strata of these sediments may be seen in the road that enters Rio Negro northwest of the railway station. These sediments are less well-consolidated than the concagua and are not as suitable for foundation use. The section shown in figure 4 may be observed along an east-west line across the ridge at the location of the cemetery.

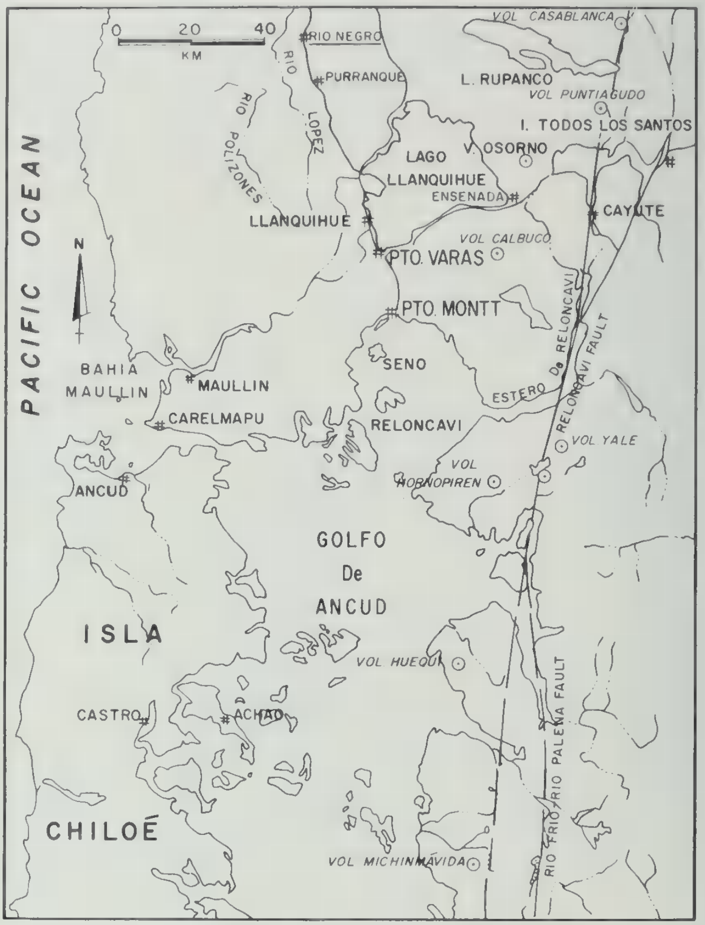

FIG. 1. Regional Map, Showing Rio Negro.

On the western side of Rio Llay-Llay appears a yellowish-red weathered conglomerate, probably the oldest formation in the vicinity. This conglomerate seems to be solid enough to afford good foundation support.

A possible loess, weathered, and in places forming columns, overlies many of the higher parts of the region to a depth of several meters. This material is marked by an irregular hummocky topography.

EARTHQUAKE DAMAGE

The damage caused by the earthquake in Rio Negro is greater than that in the country to either side.

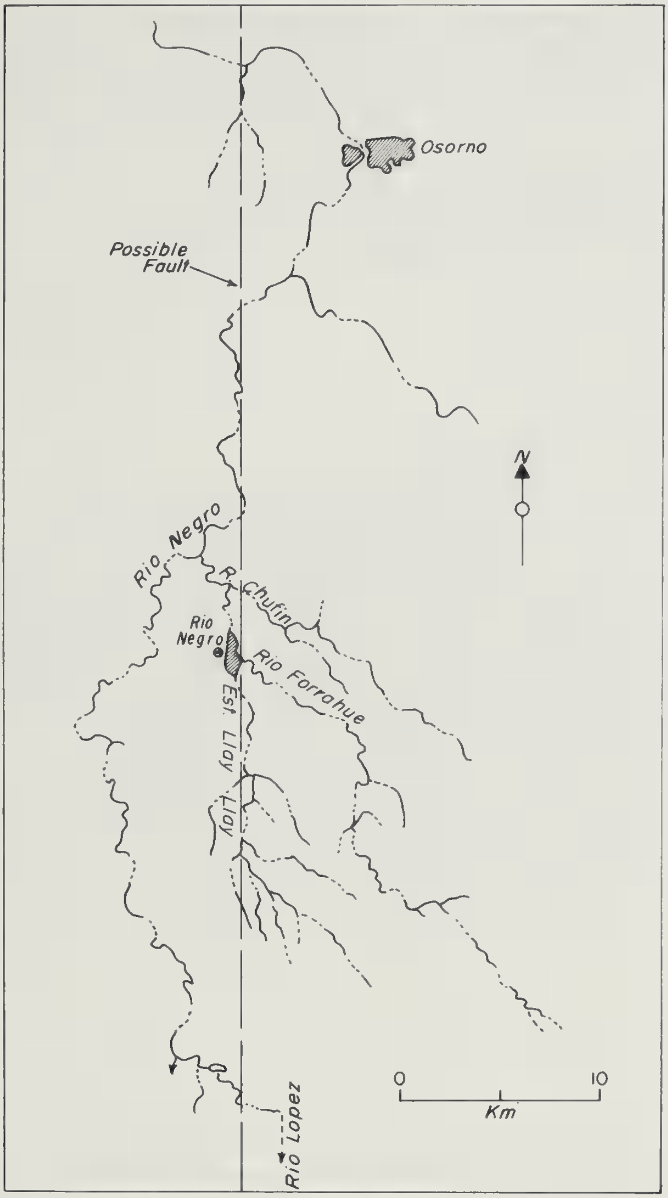

Fig. 2. Area Map of Rio Negro, Showing Possible North-South Fault.

As one approaches Rio Negro along the road from Purranque, at the last curves before arriving at the straight stretch is a group of seriously damaged houses. Sections of concrete and stone are cracked, and in places the houses have sunk a little into the soil.

In Rio Negro itself and along the high flat crest of the central ridge the destruction is almost complete, even to the concrete work surrounding the central plaza.

The Calle Pedro Montt, in the eastern part of the flat zone, passes near the edge of the slope; the backs of several houses are now over the edge of the slope and are supported only by some wooden sticks and posts. A little farther south, a concrete school under construction on the west of Calle Pedro Montt was completely destroyed. Not far from here is a wooden house of apparently one story with rather low windows. It is actually the second story of a house of which the first story of concrete, or perhaps bricks, has completely collapsed.

The church is practically intact, but the priest's house is out of plumb. In the same block as the church an elevated water tank, in the flat zone and far from the edges of the plain, suffered extensive damage (see figure 121, page 288, *Bull. Seism. Soc. Am.*, Vol. 53, No. 2): the vertical posts are not seriously damaged, but the horizontal braces are crushed.

The most serious damage occurred along the edges and on the western slopes of the ridge. There are many cracks in the soft ground, attesting to downward sliding and mass movement (figure 5).

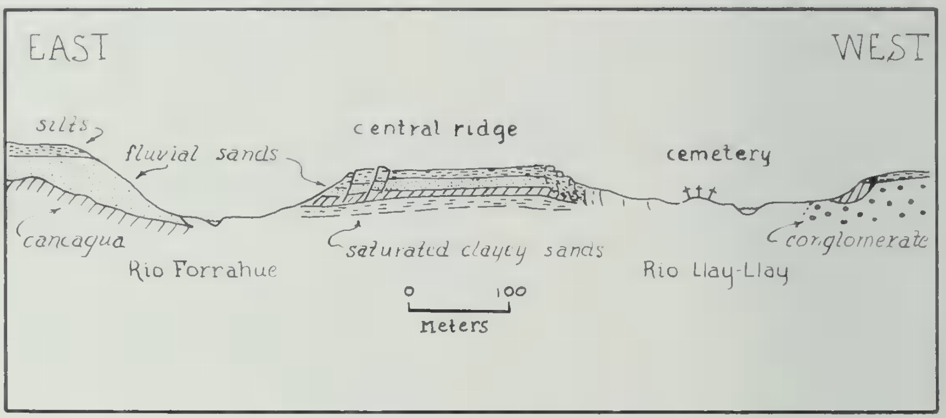

FIG. 4. Section Across Rio Negro at Cemetery.

In the valley of Rio Forrahue the destruction, although serious, is not as severe. Stone walls are cracked and some wooden houses are twisted or sunk.

Cracks in the soil appear on inclined ground, for example, to the south of the railway station and on the eastern bank of Rio Forrahue. Damage to and collapse of wooden and concrete construction occurred near the Schott Mill.

The damage is not very grave on the western slopes of the Llay-Llay River, but in the valley bottom in the vicinity of the linen factory concrete construction is destroyed and many houses are out of plumb. Some have even fallen to the bottom of the valley and into the river.

The cemetery, located on a little hill on the river banks, presents a macabre aspect. All the tombs of stone or concrete, especially the mausoleums, are heavily cracked, half tilted, or slid away and opened. The impression is that the soil jumped, displacing and overturning the tombs. Only at the edge of the river, at the foot of the hill, have the tombs not suffered damage.

Interpretation of Effects

The fact that in Rio Negro the intensity of the quake was higher than in the surrounding country leads to several possible conclusions:

1. There was a local earthquake during the main event, or as an aftershock, on a fault passing through the town near or under Rio Llay-Llay.

2. The elevated and laterally unsupported mass of the ridge oscillated more freely than the soil in the valley bottoms.

3. Mass movement took place along the ridge, the mass thereof slumping and landsliding downward.

While all three are possibly correct, the authors are inclined to favor the last two possibilities more than the first. It has long been recognized that earthquake intensity near edges of terraces, even in the absence of obvious slumping, is frequently greater than it is in flat places. Slumping obviously occurred, as attested by the cracks in the soil. Conditions in the hill were excellently suited to produce slumping, the ground having been soaked and lubricated by a recent rain.

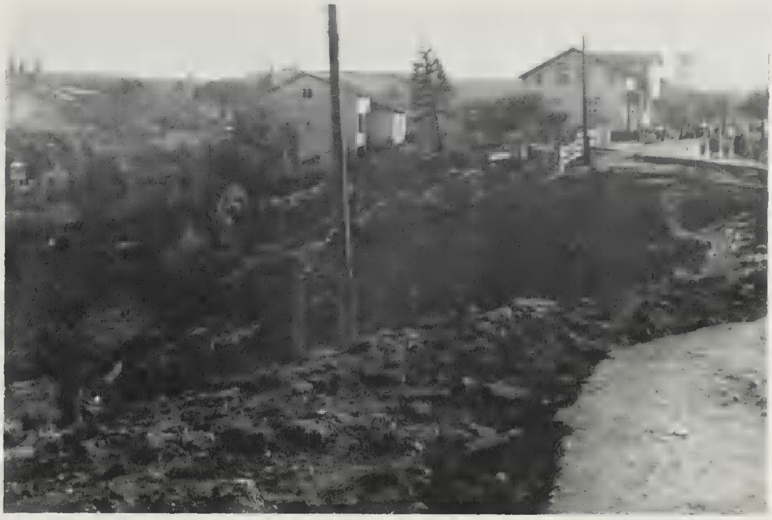

Fig. 5. General View of Landsliding in Rio Negro.

There is a good possibility, however, that an active fault passes in a north-south direction through the town, as the zone of cracking is aligned roughly north-south and is more intense on the western edge of the slope. The presence of the older conglomerate to the west does indicate a discontinuity of some sort, and this may be significant, as may also the lineation of Rio Lopez, Estero Llay-Llay, Rio Negro, and Estero Cancagua. Such a proposed fault could not have had a great deal of recent vertical movement because the floor of the central valley is roughly concordant on either side. The presence or absence of a fault cannot be proved without a great deal of more detailed regional mapping.

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MODIFICATIONS TO THE SOIL PATTERN OF SOUTH-CENTRAL CHILE RESULTING FROM SEISMIC AND ASSOCIATED PHENOMENONA DURING THE PERIOD MAY TO AUGUST 1960

By Charles Wright and Arnoldo Mella

ABSTRACT

Genesis and evolution of soils in the earthquake region is discussed and then reviewed in the light of changes induced by the earthquakes. Those effects of the earthquake that could possibly influence soils are reported on in detail. These include many field observations on the mass movement, the tsunamis, flooding, changes in land elevation and regime of rivers, volcanic eruptions, etc. A catalogue of changes, including land lost to production completes the study.

(PStA)

Introduction

The soil pattern of Chile is an expression of the extreme youthfulness of the landscape. There is no ancient land surface, as in Brazil, and no areas are known wherein the soil processes have been able to operate consistently over a long interval of time. Moreover, on many of the older and more stable sectors of the landscape, deposition of volcanic materials has, from time to time, initiated new cycles of soil building. Even in South-Central Chile, where the combined effects of weathering and leaching approach their maximum regional intensity, there are no known examples of soil of sufficient age or stability to show the maximum impress of the forces at work. In this sense, there are few mature soils in Chile.

The soil assemblage is thus characterized by a high proportion of young and immature soils, including Recent soils of the alluvial bottomland, unconsolidated coastal and riverine dune soils, and Recent volcanic soils. An interesting feature of the Chilean soil assemblage is the presence of other kinds of Recent to immature soil whose origin can only be ascribed to catastrophic earth movements associated with seismic and volcanic activity.

Features of the soil pattern considered to belong to this category include the following:

1. A sequence of Recent, sub-Recent young, and immature soils on bench terraces along part of the Chilean coastline. These terraces have mainly a gentle surface relief and occur at various altitudes ranging from 20 to 1,000 feet above present sea level. The soils on these terraces show a degree of profile development inconsistent with the prevailing weathering and leaching enviroment: the soils are too youthful for their position in the regional landscape. It is suspected that they represent soils derived from coastal drift (and associated dune loess), elevated during Recent geological time during the successive stages of uplift of a rising coastline.

The nature of the coastal drift has clearly varied from time to time, and further study may show that the nature of the coastal drift, now preserved as soil on the bench terraces, can provide valuable information about cycles of volcanic activity in the past. Volcanic activity in the Andean Cordillera has, from time to time, loaded the rivers rising on the flanks of the volcanoes with fine ejecta of varied but specific mineral composition. On reaching the sea, much of this alluvium has been turned northward by the Humboldt Current and deposited as drift material on the coastal shelf. This is a factor that produces diversity in the altitudes above sea level of the terrace soils.

This diversity notwithstanding, there is some measure of uniformity in soil profile development among terrace soils of the same elevation: over a limited sector of the coastline, terraces of the same general altitude above sea level possess soils with equivalent leaching and weathering characteristics. Using this as a rough guide, it is apparent that the Chilean coastline north of latitude 38° 30′S has been fairly consistently rising; whereas the coast south of latitude 40°30′ has been slowly sinking. Between these two points, the lower bench terraces progressively disappear (south of latitude 39°30′, only the oldest, highest terraces remain), suggesting that the axis of depression has been creeping slowly northward.

2. Sharp discontinuities in the soil profile in the alluvial soils of the coastal plain, brought about by minor, but abruptly initiated, changes in drainage conditions. In the Valdivia area, for instance, there is a sequence of river alluvium-peat-estuarine clay repeated several times in the material of the bottom lands. This could represent periodic ingressions of the sea, each followed by the gradual accumulation of estuarine clay to the point where aquatic and bog plants can colonize the area. The subsequent covering of the bog with river alluvium may represent increased erosion of the coastal range in a landscape that is slowly rising with respect to sea level. These movements are relatively minor oscillations in comparison with the appearance and disappearance of the coastal bench terraces mentioned above.

3. Local chaotic complexity of the soil pattern, apparently the result of the development of massive landslips in former times, principally along the flanks of the main river valleys traversing the coastal range.

4. Very marked development of tumultuous fan-building along sectors of the Andean piedmont. These are of two types: one, probably associated with the sudden melting of snow and ice attendant upon the reawakening of volcanic activity but not necessarily associated with seismic activity; and, another, with a distinct and characteristic microrelief that appears to be associated with the development of massive mudflows originating in seismic movements.

5. Evidence of unusual changes in the pattern of alluvial deposition in the lower valleys of the main rivers. This is, at times, due to overloading of the rivers with volcanic material during eruptions, but, at other times, the soil data suggest change in the trend of sedimentation such as might be caused by seismic activity (continental movement or activity of tsunamis) modifying conditions at the river mouths.

Change Effected in Soil Pattern and Subsequent Developments

Seismic activity was initiated at 10:02 GMT (6:02 a.m. local time) on 21 May, when a severe earthquake, with its epicenter in the Pacific Ocean west of the Arauco peninsula, caused damage in the neighboring Provinces of Concepcion, Nuble, Arauco, Bio-Bio, and Malleco. The following day, further severe shocks, with more southerly epicenters, extended the disaster to all the remaining provinces of South-Central Chile, as far south as Chiloé. The second phase of the seismic activity was accompanied by the development of tsunamis, which brought additional distress to coastal settlements between the Arauco Peninsula and the southern tip of Chiloé Island. (Fig. 1, Map of South-Central Chile, is in pocket at the end of this number.)

Damage to the road and railroad system and to telegraphic installations virtually isolated South-Central Chile from the rest of the country, and the first assessment of damage came from the reports of persons evacuated from the zone by air. Within one week, however, it was possible for teams of assessors to penetrate the affected regions by car. The following account is descriptive of the changes observed in nine selected districts (which may be located on the index map, figure 1 in the pocket at the rear of this number), visited within two weeks of the onset of the earth movements. Further changes that occurred during the ensuing year have been added to the report.

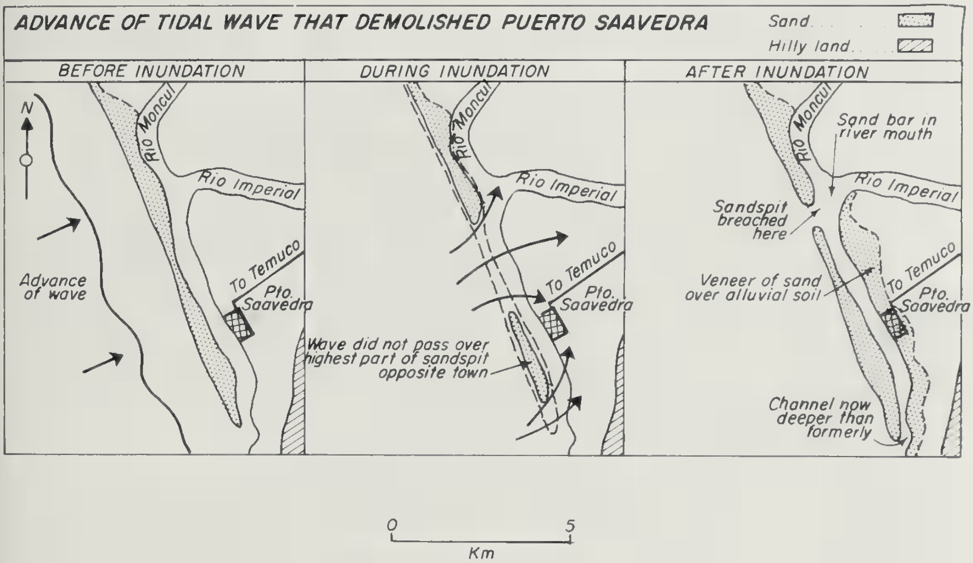
ADVANCE OF TIDAL WAVE THAT DEMOLISHED PUERTO SAAVEDRA
Sand
Hilly land
BEFORE INUNDATION
DURING INUNDATION
AFTER INUNDATION
N
Rio Moncul
Rio Imperial
Advance of wave
To Temuco
Pto. Saavedra
Wave did not pass over highest part of sandspit opposite town
Sand bar in river mouth
Sandspit breached here
Veneer of sand over alluvial soil
Channel now deeper than formerly
0
5
Km

FIG. 1 (a). Advance of Tidal Wave That Demolished Puerto Saavedra.

The districts visited, and the type of modification in the soil pattern available for study in each case, were as follows:

Puerto Saavedra—flooding of lowlands with sea water; emplacement of dune sand on alluvium. (Fig. 1(a)).

Tolten—flooding of lowlands with sea water; subsidence of land caused by compaction of lightly consolidated organic substrata; possible general subsidence of coast.

Puyehue—eruption of pumiceous ash; widespread development of landslides.

Rupanco—very extensive debris avalanches; mudflow destruction caused by lake waves; subsidence of unconsolidated sediments.

Valdivia City and Southern Valdivia—subsidence of coastline; damage by tsunamis; subsidence of unconsolidated sediments; shearing of substrata rich in allophane clays.

Northern Valdivia—damage by tsunamis; subsidence of coastline; salination of of soil water table.

Central Valdivia—landslides; alluvial deposition subsequent to release of impounded waters of Lago Riñihue.

Pellaifa—landslides; debris avalanches.

Arauco—uplifted coastline.

1. *Puerto Saavedra.* The town of Puerto Saavedra, at the mouth of the Rio Imperial, was almost completely destroyed (fig. 2) at 3:30 p.m. on the afternoon of Sunday, 22 May and during the following night, by a series of waves. The main damage appears to have been caused by the third or fourth wave at about 3:35 p.m. on Sunday. The onset of inundation was comparatively gentle and the population, already expectant of unusual tidal phenomena, was able to assemble on the slopes of the hills behind the town. Since the day was fine and the sea otherwise calm, the gradual destruction of the town was under continuous observation as long as the light lasted. Most observers agreed that after an initial retreat of the sea water, there was a gradual flowing in and that the larger waves, which caused most of the damage, were not more than a few meters high. It appears that the town was flooded to a maximum depth of about $3\frac{3}{4}$ meters, and within 24 hours from the onset of inundation, the land was again clear of water, except for the many pools occupying the low-lying places.

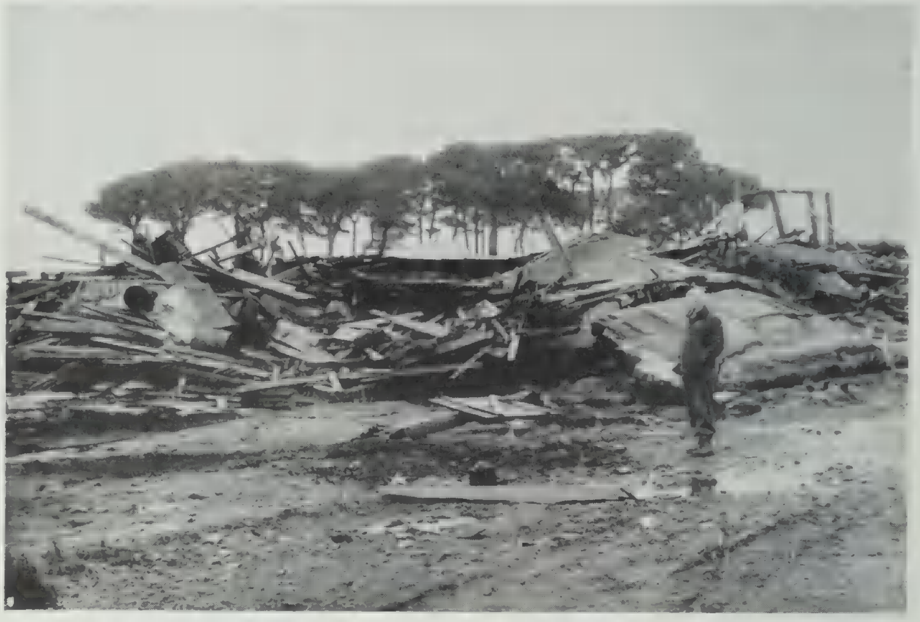

FIG. 2. Main Street of Puerto Saavedra, Photographed on 1 June After Passage of Tsunamis of 22 May. View looking inland. (Photo L. Duharte)

Many of the buildings on the seafront were wholly or partially destroyed by direct wave action, and the single row of macrocarpa trees planted as shelter from the wind provided but little protection for the buildings. However, buildings farther away from the shore, with protection of trees, usually escaped demolition or even serious damage. Without the protection of trees, the battering action of the debris from the demolished buldings of the seafront carried inland by the waves caused almost total demolition. Since few houses had the requisite shelter by trees, almost the whole town site was eventually swept clean. The protective effect of even a few trees in in areas remote from the actual seafront was very striking. Most of the buildings were constructed of wood and were easily demolished. Some were lifted up and overturned before breaking up.

The impact of the sea was not equal along the whole coastal strip. The town of Puerto Saavedra (fig. 1a) is sheltered by a long sand spit—a prolongation of the coast from near the mouth of the Rio Moncul, which lies to the north. Between Puerto Saavedra and the sand spit, there is a channel some 1 ½-km wide, carrying water from the Rio Imperial to the sea. When the great tsunami swells from the open ocean approached the shore, they engulfed all but the highest parts of the sand spit and moved on across the channels toward the mainland and Puerto Saavedra. In one place opposite the Rio Imperial, in passing over the sand spit, the sea broached the sand barrier, and the Rio Imperial can now empty directly into the sea without following its former channel past the site of Puerto Saavedra. Following the broaching of the sand spit, there was more or less free passage of waves from the open sea, and the town was subjected to wave action from two directions, southwest and northwest. Where these two systems of waves met, the action of the sea was particularly destructive.

It is important that this broaching of the sand spit and other local modification in the coastline be studied closely, because all the evidence suggests that there will be a building up of a new sand bar, or at least some deposition of sand from the old sand spit across the new mouth of the Rio Imperial. This could have serious repercussions on the lowlying agricultural land in the valley of the Rio Imperial because in the event of heavy rain over the cordillera, it is unlikely that the river will be able to discharge the extra volume of water at its customary rate. Abnormal flooding of valuable agricultural land may be expected in this valley for some years. (This actually did happen in May and June 1961.)

There were few permanent changes in the soil of the plain adjacent to the former site of Puerto Saavedra. These soils are sandy loams or, in some places, gravelly clay loams, and their normal water table lies 80 cm to 1 meter below the surface. Below this depth, the soils are poorly drained and strongly mottled; they are fairly free-draining above the level of the permanent water table. These soils were flooded with sea water for about 24 hours, but inspection pits dug into the center of the affected area one week after their inundation showed that earthworms and grass-grub larvae were alive and well. The pastures did not seem to be greatly affected, as they were still green and putting out new leaves. Bare soils, such as in fields where the potato crops had been harvested or where sugar beets were growing, suffered some superficial erosion, but the amount of soil lost amounted to only a few centimeters. A few of the shallow drainage ditches in the area were filled in, but most of the drains are now functioning normally. By 1 June, the soil water table had almost returned to its normal level, and instead of the land now being lower, it appeared to be slightly higher than before. There was some redistribution of sand and silt from the actual coast, these materials being carried inland and deposited near the more clayey soils of the center of the plain; but, again, this amounted to only 1 or 2 cm. The chief agricultural damage was to fences and other farm installations. Soil samples collected one week after inundation showed that these soils still contained some extra salt, but it seems there had been sufficient rainfall between 23 May and 1 June to wash out most of the added salt.

From rapid examination of the coastal plain in the vicinity of Puerto Saavedra, it would seem safe to conclude that there has been no permanent damage to the agricultural potential of the soils. Attention should be drawn to the possibility of severe flooding of the lowlands between Puerto Saavedra and Nueva Imperial, 40 km inland. The new configuration of the coast at the mouth of the Rio Imperial and its implications with regard to possible change in the pattern of sedimentation at the river mouth need to be studied in detail. It is likely that the former channel of the river, which passes to the south of Puerto Saavedra, will become considerably deeper opposite the site of the former port installations.

2. *Tolten*. The town of Tolten is located near the mouth of the Rio Tolten, approximately 100 km southwest of Temuco, and near the last major bend made by by the river before reaching the sea (figure 1). The town is located on an alluvial plain and is nearly 2 km inland from the bank of the river (figure 1 b). At this point, the river channel runs inside of and is protected by a sand spit $1\frac{1}{4}$ km wide. The presence of this sand spit and the wide extent of the alluvial plain undoubtedly protected the town of Tolten from the type of extensive damage suffered by Puerto Saavedra, although the sand spit opposite Tolten is somewhat lower in elevation than that opposite Puerto Saavedra.

As in the case of Puerto Saavedra, the sea retreated and then began to rise steadily and rapidly at 3:15 p.m. on Sunday, 22 May, inundating the town to a depth of about $1\frac{1}{2}$ meters. The water then subsided and, fearing another deeper inundation, the people moved to the tallest available buildings and to trees. A second inundation began after a lapse of about 10 minutes, and the water reached a maximum depth of about 3 meters. This inundation took longer to subside, and many of the wooden houses were washed from their supporting blocks. Actually, some houses, weakened or damaged by the earthquake about 30 minutes before, probably began to disintegrate when the sea first entered the town. Unlike Puerto Saavedra, where the sea caused almost all of the damage, in Tolten the earthquake damaged many houses and produced large fissures in the soil. The inundation that followed partially filled in many of these fissures, but the damaged houses collapsed. Eyewitnesses stated that the main swell broke against the protecting sand spit and the sea passed over the sand only in the lowest part, opposite the site of Tolten. Undoubtedly, the force of the wave had diminished greatly in passing the sand barrier and was further reduced while passing the 2-km wide strip of alluvial plain. The pattern of destruction was quite unlike that at Puerto Saavedra; the arrival of the water was comparatively slow—as in an abnormally high tide—and there was little battering action by floating debris.

For a time, sea water covered all the low-lying alluvial plain between Tolten and the adjacent coastal range. The soils of the alluvial plain contain more clay than those of Puerto Saavedra. However, as in the case of Puerto Saavedra, the soils appear to have suffered little permanent damage from their brief immersion in sea water. When visited on 24 June, the earthworm population was still alive, and the only pasture plants that appeared to be dead were the clovers. The water table had returned to its normal winter level (at the top of the mottled zone), and the land in the immediate vicinity of Tolten did not appear to have altered in elevation with respect to the level of the sea.

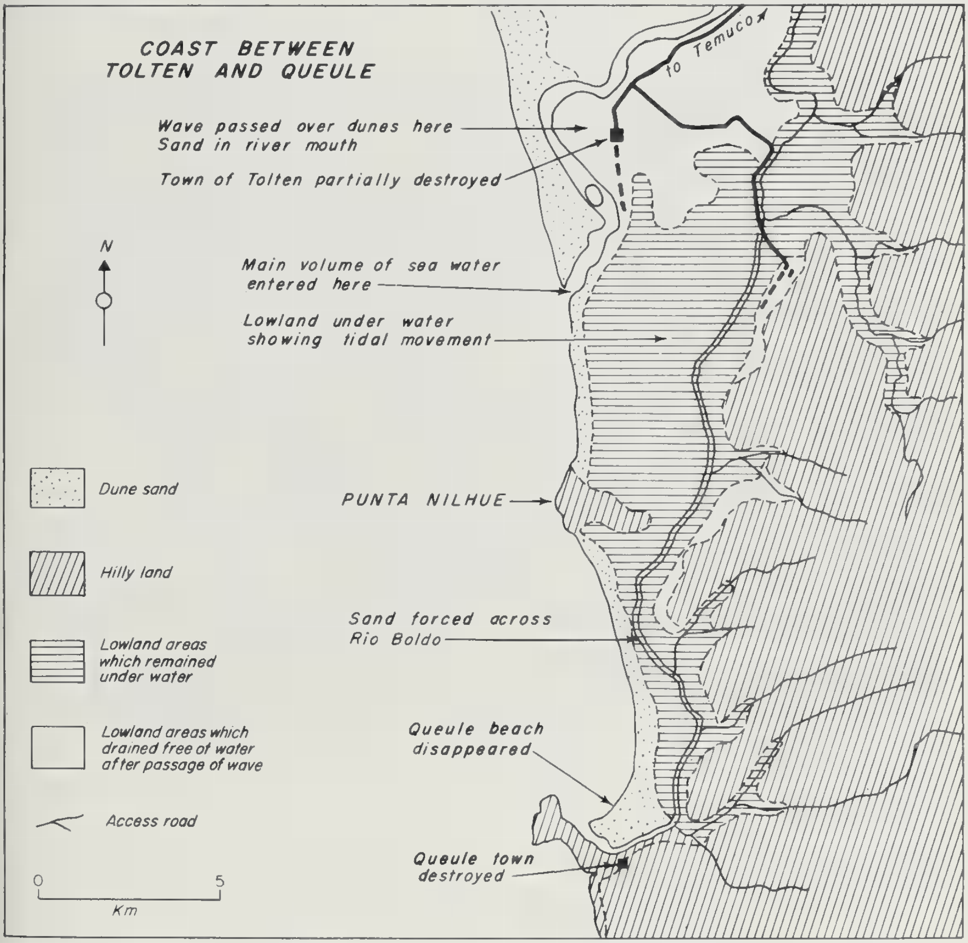
COAST BETWEEN TOLTEN AND QUEULE
to Temuco
Wave passed over dunes here
Sand in river mouth
Town of Tolten partially destroyed
N
Main volume of sea water entered here
Lowland under water showing tidal movement
Dune sand
Hilly land
Lowland areas which remained under water
Lowland areas which drained free of water after passage of wave
Access road
PUNTA NILHUE
Sand forced across Rio Boldo
Queule beach disappeared
Queule town destroyed
0
5
Km

FIG. 1 (b). Coast Between Tolten and Queule.

Between the site of Tolten and the foothills of the coastal range, there is an area of low-lying land some 5 to 6 km wide, normally lying about 1 to 2 meters above the mean low tide level. On this part of the coastal plain, the soils are mottled peaty clays and peat loams. This lowland area filled with sea water at the time of the tsunamis, and after an initial flooding to a depth of 2 to 3 meters (in the deepest parts), there was only a recovery of 60 cm in the level during the succeeding 8 days. Most landowners are convinced that the land has now sunk at least 1½ meters below its former level (figure 3). They point out that the water on their land fluctuates regularly in depth by some 30 cm with the tides. Accurate measurement of the level of this land with respect to mean tide levels is in progress, but even today, 12 months after the earthquake, the land remains beneath a lake of brackish water.

Evidence from Queule, a coastal port at the mouth of the Rio Boldo where a grotto cut in the cliff is said to be 1 meter 80 cm closer to mean sea level than before the earthquake, provides more positive indication that there was indeed a general subsidence in the level of the coastal region south of Tolten. This may be the reason why the Tolten lowlands are no longer draining normally. There are, however, two other points to be kept in mind. The first is that, as in the case of Puerto Saavedra, the offshore sand bars have altered their form and distribution. In one place, to the south of Punta Nilhue, the coastal dunes were breached by the tsunamis, and the sand is now partially blocking the lower reachs of the Rio Boldo. Thus, both the Boldo and the Tolten rivers are now partially obstructed by sand, and, during periods of heavy rain, further flooding of the lowland may be expected. The second possibility to be kept in mind is that, during the shaking action of the earthquake, unconsolidated sediments tend to pack closer together. A clear example of subsidence from this cause was seen 5 km northeast of Tolten, where Recent sandy alluvium of about 1 meter 50 cm depth overlies organic materials accumulated in an ancient swamp. During the shaking action of the earthquake, these organic deposits compacted, and an arcuate pattern of vertical fissures developed in the over-

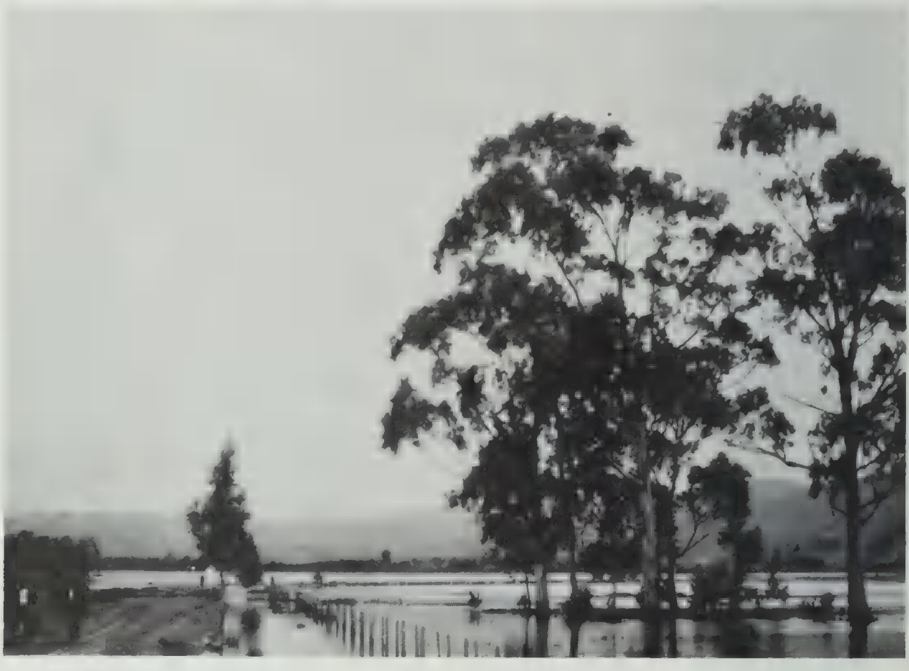

FIG. 3. Flooded Lowland Near Tolten Photographed on 2 June 1961. Twelve months later, the only differences noted were that the trees had died and a temporary access causeway had been constructed across the flooded plain.

lying alluvial material, marking out the limit of the area of subsidence (figure 4). Much of the Tolten and Boldo plains are underlain by similar peaty materials, and some of the apparent change in the level of the land may be due to local subsidence caused by the decomposed, peaty substrata being shaken into a more compact mass.

The situation of the farmers on these inundated lowlands is serious. There were heavy stock losses on the smaller holdings, and much first and second class agricultural land has now been under water for more than a year. The heavier textured soils have suffered considerable structural damage from their prolonged immersion in, first, sea water, and now a brackish mixture of sea water and river water. It was recently estimated that more than 10,000 hectares of lowlands are still inundated along the southern sector of the coastline of the Province of Cautin.

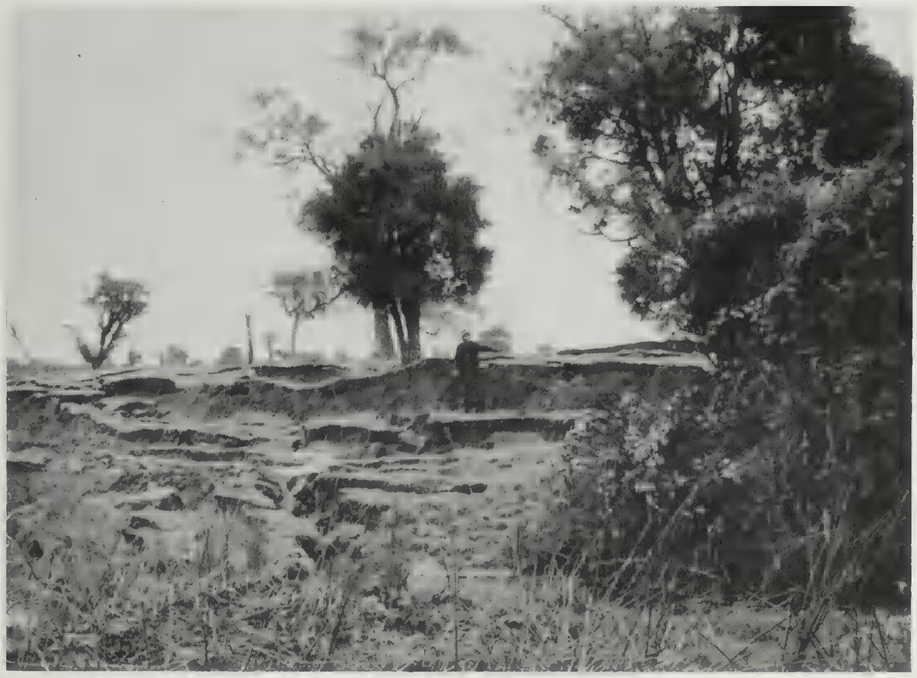

Fig. 4. Fissured Ground Near Tolten, Marking an Area of Subsidence Produced by Packing of Unconsolidated Peaty Sediments Below Alluvial Soil. (Photo L. Duharte)

3. *Puyehue*. This region lies at the eastern end of Lago Puyehue and extends up the valley of the Rio Golgol as far as the Argentine border (figures 1 and 1c). In general, it is a region of narrow, fertile valleys with steep slopes formerly covered with forest up to the snowline (at about 1,990 meters). Before the earthquake, much of the landscape had suffered severely from erosion as the result of efforts to develop agriculture in the region, and fire had damaged much of the natural forest at higher elevations.

Lago Puyehue is 212 meters above sea level, and the main valley of the Rio Golgol rises fairly gently for a distance of about 22 km. The valley floor, occupied by a narrow strip of Recent alluvium, is flanked by colluvial soils accumulating along the foot of the steep valley sides and partially burying a system of old alluvial terraces. The valley is somewhat wider in the vicinity of Anticura, 22 km east of Lago Puyehue, and, here, there is a more extensive development of alluvial fan soils. Agriculture in this valley is mostly practiced on small mixed farm holdings, ranging from 50 to 150 hectares; the total population in the valley is probably less than 800 persons. The valley of the Golgol is carved in mainly andesitic and basaltic rocks

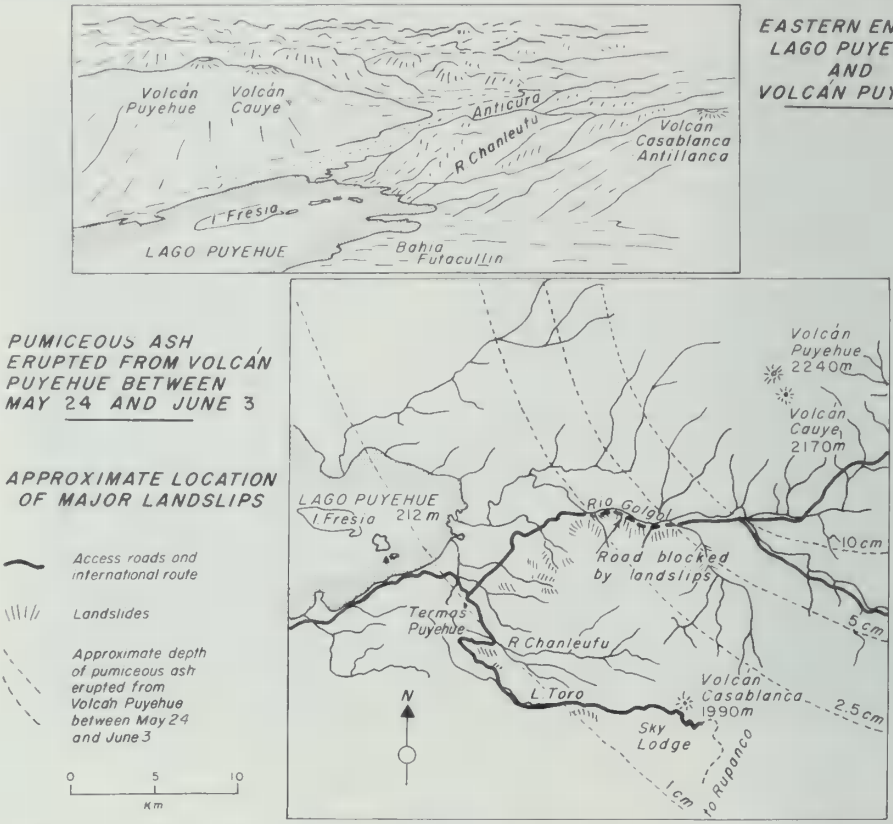
EASTERN END OF LAGO PUYEHUE AND VOLCÁN PUYEHUE
Volcán Puyehue
Volcán Cauye
Anticura
R Chanleufu
Volcán Casablanca Antillanca
I Fresia
LAGO PUYEHUE
Bahia Futacullin
PUMICEOUS ASH ERUPTED FROM VOLCÁN PUYEHUE BETWEEN MAY 24 AND JUNE 3
APPROXIMATE LOCATION OF MAJOR LANDSLIPS
Access roads and international route
Landslides
Approximate depth of pumiceous ash erupted from Volcán Puyehue between May 24 and June 3
0
5
10
Km
N
LAGO PUYEHUE 212 m
I. Fresia
Volcán Puyehue 2240m
Volcán Cauye 2170m
Rio Golgol
Road blocked by landslips
10 cm
5 cm
2.5 cm
1 cm
Termas Puyehue
R Chanleufu
L. Toro
Volcán Casablanca 1990m
Sky Lodge
to Rupanco

Fig. 1 (c). Eastern End of Lago Puyehue and Volcan Puyehue Covered With Pumiceous Ash.

lying between the two main volcanic centers of Puyehue and Antillanca. The mountainous landscape surrounding the valley is dominated by Volcan Puyehue (2,240 meters), about 10 km to the north, and Volcan Casablanca (1,990 meters), some 13 km due south.

The farming population was formerly served by one road, which also connected with Argentina. A few moments after the earthquake at 3:15 p.m. on Sunday, 22 May, this road was blocked by a series of landslides that engulfed sectors of the road, carried away bridges, and diverted streams so that they eroded away additional sections of the road.

The isolated valley community was further alarmed at 3:15 p.m. on Tuesday, 24 May when an explosion occurred near the crest of Volcan Puyehue, apparently located in or near a parasite cone called Cauye. The exact location of this eruption was observed from several points, for the afternoon was clear until the moment of the eruption; but there is some difference in local opinion as to whether the explosion actually occurred in, or merely near, the crater Cauye. The eruption steadily increased in violence and continued for seven days. A further brief eruption occurred in March of the following year.

Little volcanic ash fell in the Golgol area during the first day of the eruption. The sky became obscured and the air became charged with sulphurous gases, but a strong westerly wind was blowing and most of the volcanic ash was carried over the cordillera toward Argentina. Messrs. A. Delley and S. Barraclough of the Technical Assistance Mission of FAO in Chile, who were passengers on the regular LAN flight from Punta Arenas to Santiago on the same Tuesday afternoon, report that the plane flew through a wide belt of ash-filled air, and, on landing at Mendoza, the pilots found that most of the paint on the leading edges of the fuselage of the plane had been completely eroded.

The following day (Wednesday, 25 May) was calm. The column of steam and ash over Volcan Puyehue extended vertically upward to a great height. In early morning, fine black ash, and later very fine white sand, began to fall on the landscape as far west as Cudico (near La Unión) and as far south as Puerto Octay, at the north end of Lago Llauquihue. The total amount accumulating during the day, at these points (80 to 90 km distant from the vent), was only a few millimeters, but all the vegetation and buildings had a greyish color from the layer of volcanic dust. At the Custom Station near Termas Puyehue, a total depth of 7 mm was recorded. Ten kilometers nearer the volcano, in the Golgol valley, more than 1 cm accumulated, but all the material falling on landscapes to the west of the vent during this early phase of the eruption was sand, of a fine to medium texture.

The mountain became obscured by a cloud during the latter part of Wednesday and remained invisible for most of the succeeding week. Small amounts of ash fell intermittently over the landscape between Osorno and Puyehue on Thursday, but, either late on Thursday night or early on Friday morning, an increase in the frequency of earth tremors and subterranean noises heralded the appearance of a shower of coarse pumice fragments. These were mainly oval-shaped or rounded, light, porous stones between $\frac{3}{4}$ and $1\frac{1}{2}$ cm in size. These coarse materials fell over the landscape within 15 km to the west and southwest of the vent, and probably most of this coarse shower fell on the slopes of the cordillera to the east. No large pumice fragments fell at Termas Puyehue, or at any point further to the west. About $1\frac{1}{2}$ cm fell at Puente Negro, 10 km east of Termas Puyehue, while further up the Rio Golgol about 4 to 5 cm was reported. No ash fell on the landscape between Osorno and Termas Puyehue on Saturday. A little fell on Sunday, 27 May, and the activity of the vocano was apparently on the wane. During the strong easterly wind experienced in this region on 10 and 11 June, a small additional dusting of ash (less than 1 mm) was observed in Rupanco and Osorno. Thus, during the three weeks following the intial phase of the eruption from Volcan Puyehue, a total of only 1 cm was recorded by the carabineros stationed in the Customs House near Termas Puyehue, and the 7.5-cm boundary of the new volcanic ash deposit lies about 10 km west and south of the actual vent. The greatest extent of the new volcanic material will certainly lie to the east, over the Andean Cordillera, and in Argentina.

A sample of fresh ash collected by the officials in charge of the Customs House appeared to be mainly fine pumice sand. Collecting samples of the new ash from the actual surface of the soils proved to be quite difficult. Over 10 points of rain had fallen on 25, 26, and 28 May, and again on 1, 3, 5, and 6 June. This amount of rain proved to be adequate to disperse the ash on the landscape, and only very small amounts could be scraped up from particularly favorable sites, such as fissured rock surfaces, tree stumps, and horizontal logs. Samples of this type were collected over a radius between Osorno and the Golgol valley. Since the only route up the Golgol valley was effectively blocked by landslides, no samples could be collected beyond Puente Negro; but, fortunately, samples of coarse, stony pumice were found and collected from this locality. Additional samples were collected from places nearer the volcano when the road was cleared for vehicular traffic in March 1961.

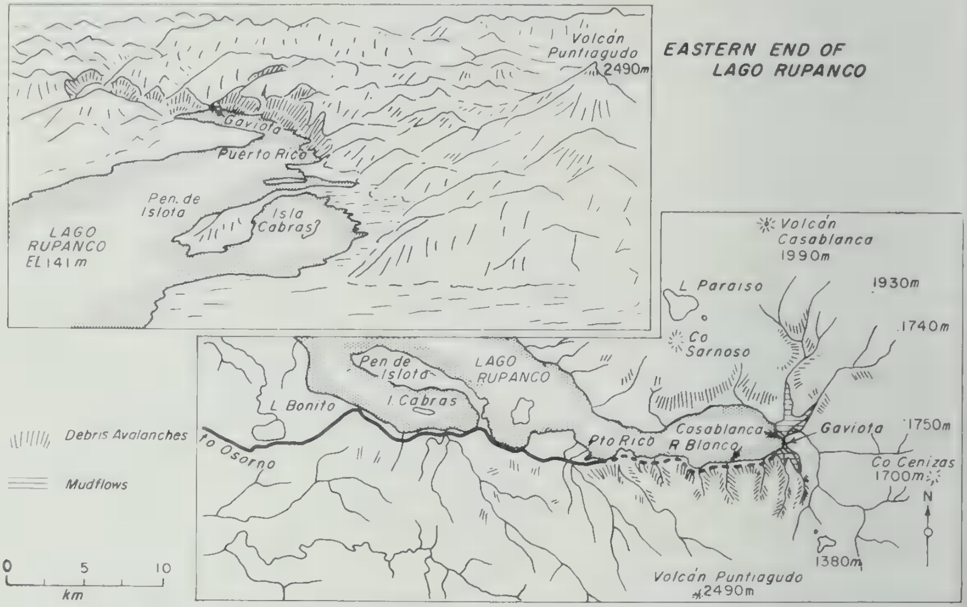

FIG. 1 (d). Debris Avalanches and Mudflows Near Eastern End of Lago Rupanco.

During the first few days of the eruption, most of the farmers in the valley were evacuated by helicopter or escaped on foot across the landslides. These landslides are composed mainly of ancient volcanic ash material, with boulders of andesitic and basaltic flow rocks. In their natural state, these steep valley sides are mantled with 2 to 3 meters of volcanic ash, showing clear layering, with successive layers of scoria, fine sand, coarse pumice, allophane-rich silts and loams, etc. The natural mechanism that caused this mantle of ash to peel away, and the events that followed, appear to be the same as those investigated at Lago Rupanco. In the Golgol valley, the debris avalanches (Sharp, 1938) are not as widespread or of so great an individual extent as at the head of Lago Rupanco. In addition to the destruction of the only access road, damage by landslip debris to the agricultural land in the Golgol valley has been considerable. On the other hand, deposition of ash from the Puyehue eruption appears to have occasioned little damage to the agricultural resources of of the region. The ash samples collected have been checked for toxic or other possible harmful factors likely to affect the health of livestock, but nothing of this nature was found.

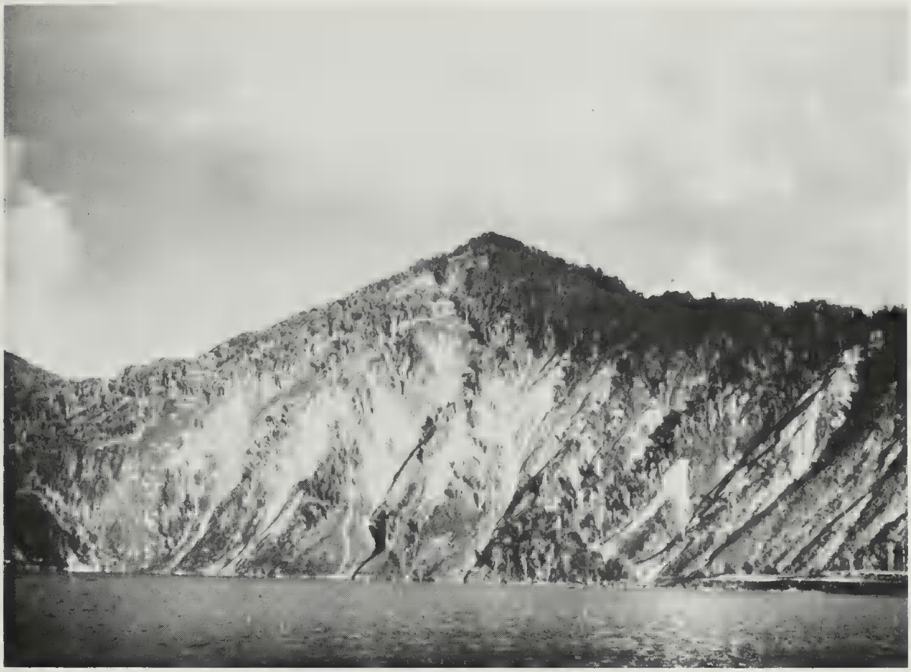

FIG. 5. Scarred Face of Slopes Bordering Lago Rupanco Where Landslides Developed During the Earthquake of 22 May. Fifteen persons were overwhelmed on the road and swept into the lake in the sector shown in the photograph. White scars indicate removal of the volcanic ash mantle to expose andesitic rock; darker scars still have some weathered scoria clinging to the steep slopes. The ancient volcanic cone, Puntiagudo, can be seen in background.

4. *Rupanco.* At the eastern end of Lago Rupanco (figs. 1 and 1d) some 125 persons perished within a few minutes during the earthquake at 3:15 p.m. Sunday afternoon, 22 May. About half this number were families belonging to the Gaviota farming settlement established by the Caja de Colonizacion, and the rest were laborers engaged in constructing a road around the lakeshore to link this farm settlement with Osorno city. Some of the victims were swept into the lake by landslides (fig. 5) from the steep slopes bordering the lake; others were enveloped in rapid-moving rivers of mud, rocks, and trees that developed wherever landslides converged.

The soils of this region (fig. 6) are formed from successive layers of volcanic ash; typically, the top 40 cm is pale colored and pumiceous while the lowermost horizon consists of 40 to 80 cm reddish-brown weathered scoriaceous coarse gravel.

Between these two thick porous horizons, there may be one or more thin layers of fine andesitic volcanic ash weathered to the stage when a high proportion of allophane clays are present. When moist, these allophane-rich horizons are slippery and greasy; when dry, they have many of the properties of very fine sand. These laminated soils, derived from alternating layers of volcanic ash of diverse origin, occur over the whole of the landscape; even slopes of 40 degrees and upwards have an ash mantle usually thicker than 1 meter. Rarely do the underlying andesitic-flow rocks protrude through this mantle.

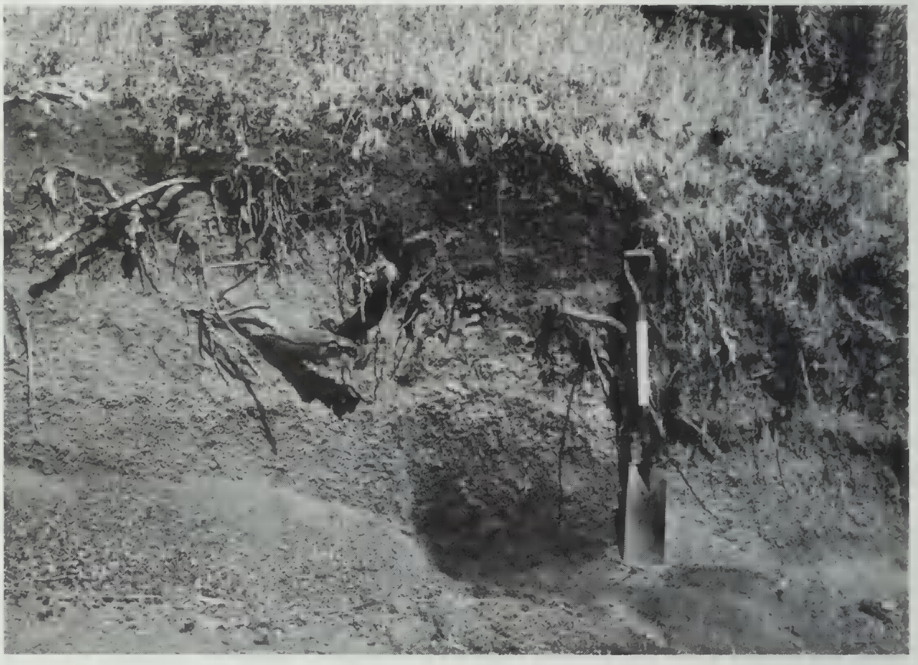

Fig. 6. Laminated Volcanic Ash Soils Typical of the Rupanco Region. The dark colored surface soil is pumiceous sand. This is underlain by loamy fine sand of andesitic origin, followed by coarse pumice gravel and a layer of silty clay loam rich in allophane clay (level with bottom of spade). Note shown in photograph is the thick layer of weathered scoriaceous gravel that underlies the allophane-rich layer.

The rainfall of the region is abundant and well distributed throughout the year, and even the steepest slopes are able to support a forest cover. Up to about 1,200 meters, the commonest trees in the forest are olivillo (myrceugenia corraefolia) and tepa (tepulia stipularis) of the myrtle family; ulmo (eucryphia cordifolia) of the eucryphiaceae; and the chilean laurel (laurelia sempervirens) of the monimiaceae. In the volcanic ash soils of this region, all these species have very shallow rooting (figure 7). The top soil is laced through by a mass of large and small roots, often fused together where they intersect, forming a tough superficial root network, which undoubtedly helps to hold the soil in place on steep slopes. This predilection toward superficial rooting is probably connected with periodic renewal of plant nutrients at the soil surface when the neighboring volcanoes are erupting.

There is abundant evidence that this plant-soil landscape system is under tension even under strictly natural conditions. Steep slopes carrying virgin forest show the same pattern of erosion as has been observed in the fiordland region of New Zealand (Wright and Miller, 1952). In the course of time, individual trees become too large for the steepness of the slope, and on breaking away they start an avalanche of trees, soil, and rocks that cuts a long narrow scar in the forested mountainside. Trees slowly reclothe this scar, and the net result is a forest composed of communities of varying ages, with marked vertical, or "striped," patterns.

When the forested slopes are burned, either accidentally or as a stage in the process of replacing forest with pasture, the superficial root network is destroyed and marked instability of soil develops, especially on slopes steeper than 25 degrees. Actual land-clearing operations usually stop if the slope is more than 25 degrees, because the farmers are well aware of the instability of the soil; but fire employed in clearing the land frequently escapes and burns the forest on the steeper slopes nearby. Accelerated erosion is evident on much of the land wholly or partially cleared, and takes the form of small crescentic slips, land slumping, or landslides, which are usually of greater width but smaller length than those that are a feature of the normal erosion. Any abnormal seasonal condition (such as a very dry period followed by a few days of heavy rain or an abnormally wet winter season) starts the cycle of accelerated erosion on land cleared or partially cleared by farmers.

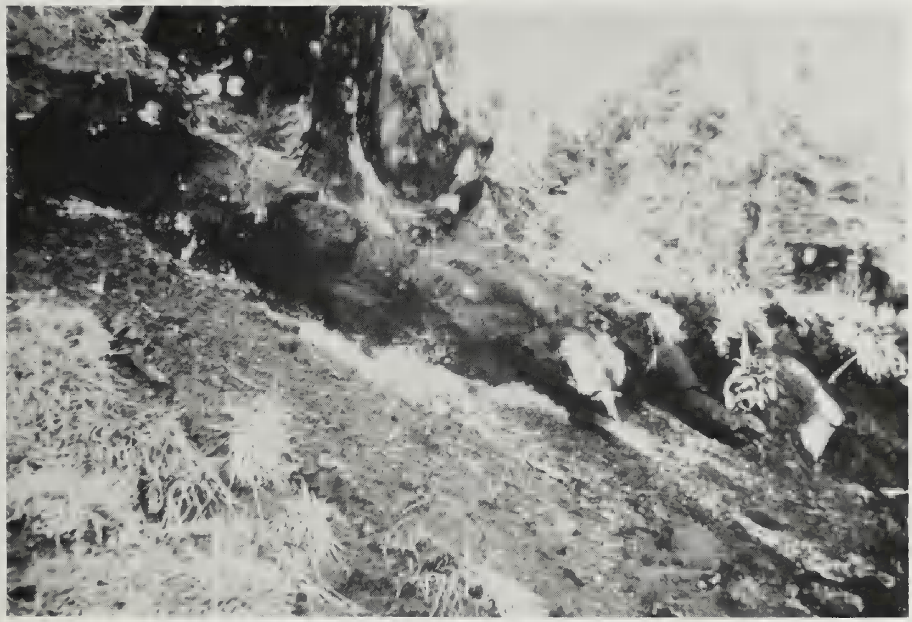

FIG. 7. Main Roots of Olivillo (myrceugenia corraefolia) Are Near Surface and Do Not Penetrate Into Gravelly Pumice and Scoria Layers of the Subsoil.

In the past, in this part of the Rupanco region, much time and labor have been lost in trying to establish pasture on the hill slopes—even wheat crops have been sown—because the strip of easily cultivated land along the lake side is far too small to permit the settler to develop an economic farm unit. Most holdings are between 50 and 200 hectares in extent, and usually less than $\frac{1}{10}$th of this area consists of land of easy relief, which can be relied upon to remain in a stable condition when the forest is removed. Under such conditions, farmers must try to get as much production as possible from the hill and steepland soils; but on soils such as these, formed from laminated ash beds, the risk involved is always extremely high.

The impact of the earthquake on Sunday, 22 May, was sudden and disastrous. The previous summer had been a dry one and the soils were in an abnormally dry condition. On Friday the 20th, there had been a mild earthquake which, as several farmers noted, caused widespread fissuring on the soil (figure 8). Heavy rain fell all day, and one may assume that this rain quickly saturated the porous layers in the subsoil and thoroughly wetted the allophane-rich layers. Several minor landslips occurred on Friday night and more on Saturday. The main earthquake came on Sunday, causing the simultaneous development of hundreds of major debris avalanches. In areas where the forest had been burned, these landslips started from the highest crest of the slope; where the forest was in a more or less natural state, they started from the highest point reached by land clearing operations. Many avalanches fell a total distance of more than 1,000 meters, down slopes averaging 40 degrees. In some cases, whole mountainsides 5 to 8 km wide were suddenly and completely stripped of vegetation and soil. In places, this enormous mass thundered

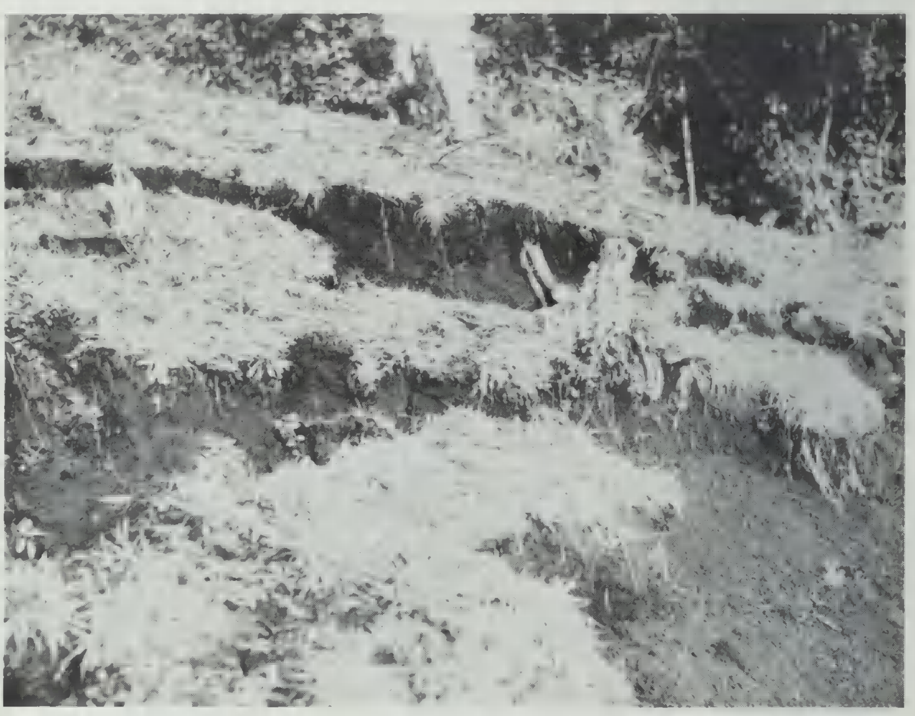

FIG. 8. Fissuring of the Soil and Slumping Produced by Heavy Rain Following the Mild Earthquakes of 20 May.

down directly into the lake, sweeping houses and people along with it. In two places, at the head of the lake, debris avalanches from several slopes converged and formed enormous mudflows (figure 9), which advanced with surprising rapidity over the intervening rolling land and then finally discharged into the lake. People, animals, houses, etc. in the path of these mudflows were engulfed and churned among the mixture of trees, rocks, and soil. Many of the largest trees were completely stripped of their bark, and some were splintered into matchwood. There is abundant testimony to the power and irresistible force of these mudflows. Eyewitnesses, who escaped by the lucky chance of being on an island-fragment of the landscape that remained in place, agree that the mudflows advanced with a wavelike crest (fig. 10) and that a man seen galloping on horseback could not move fast enough to escape. At the time of the earthquake, the day was fine and clear; but within seconds of the fall of the debris avalanches, the air was filled with fine droplets of water and a thick mist enveloped the whole of the upper end of the lake for the rest of the day. The impact of the debris avalanches produced a shockwave that caused some houses to jump several meters into the air. A wall of water rose from the northeast corner of the lake, swept across the settlement of Gaviota on a terrace 12 meters above normal lake level, and then ricocheted from side to side down the lake until its force was expended in the vicinity of the peninsula of Islota. In the center of the lake, this wave and succeeding backwash waves produced nothing more than a sharp swell; but along the lake shore where the waves

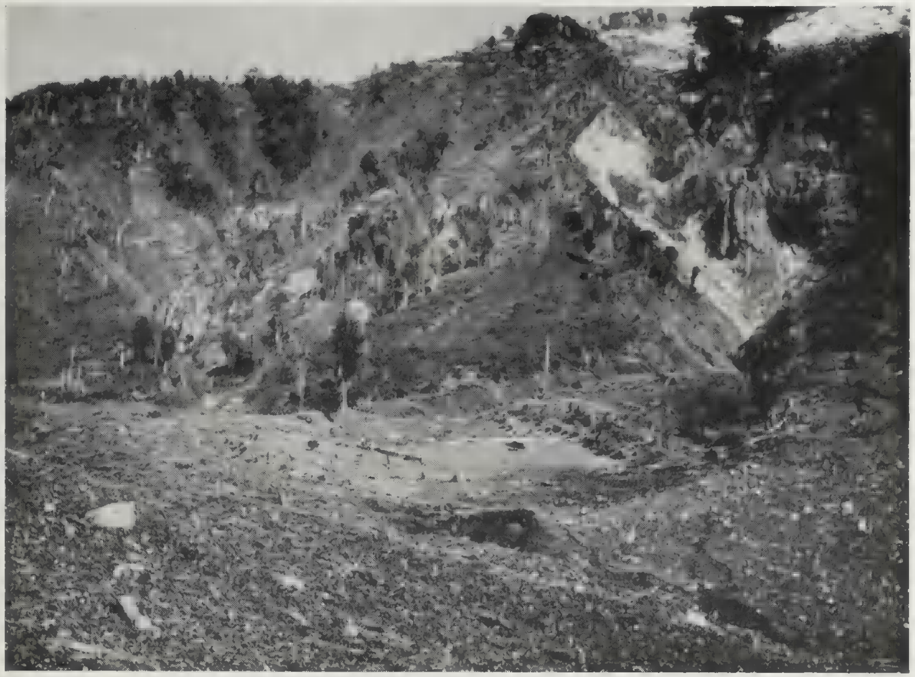

FIG. 9. Converging Debris Avalanches Produced the Mudflows That Engulfed the Settlement of Gaviota on Lago Rupanco.

broke with great force many small houses and many of their occupants were washed away. This was the catastrophic erosion and associated phenomena that practically obliterated the settlement of Gaviota on Sunday, 22 May, 1960.

There remains the scientific inquest (Wright and Mella, 1961). In the first place, the layer formation of the soils themselves, with an allophane-rich layer sandwiched between two porous water-holding layers, provides a basic element of instability. The history of land slipping in the region confirms this instability. The pattern of the catastrophic erosion indicates that farming operations were partly responsible. Examination of steep forested slopes where no actual landslips occurred showed that fissures were present in the soil but that, even though many elements in the superficial root network had torn apart, the meshwork was still strong enough to hold the soil mantle in place. Further examination of the upper zone of deforested slopes, which only slipped a short distance, confirmed that the initial fissures were quite shallow, penetrating through topsoil and pumice horizons and ending in the allophane-rich layer. The examination was carried out during heavy rain, and care had to be taken not to set off further landslides since much of the soil's mantle was still highly unstable. It is not difficult to reconstruct the origin and development of the debris avalanches set off by the earthquake.

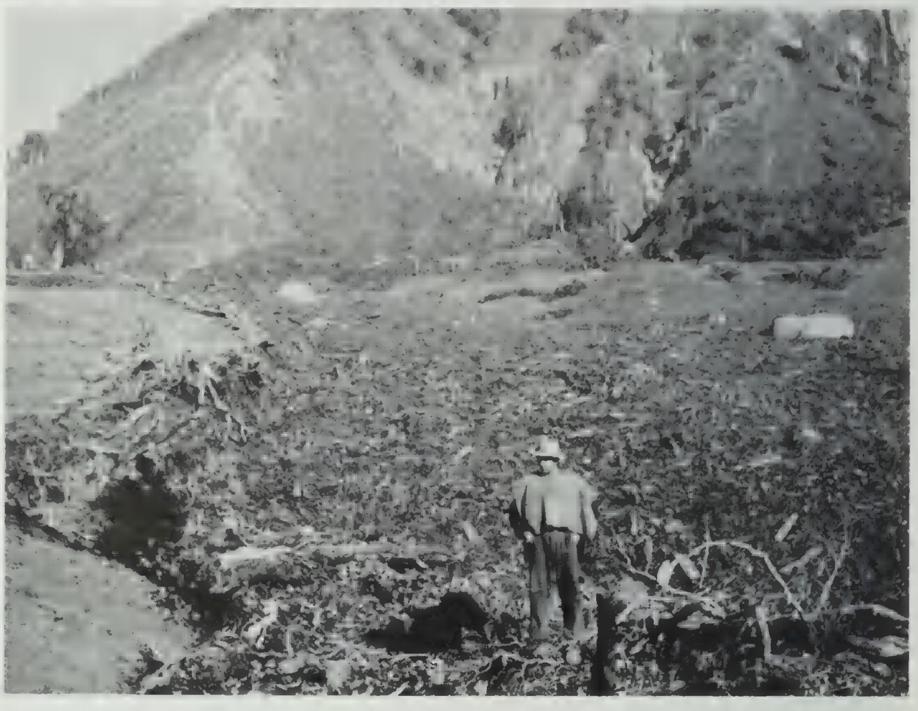

FIG. 10. Passage of Wave-Like Crest of Mudflow Leaves Debris Piled Along Flank. The large andesite rock to the right in the middle distance has a volume of about 100 m^3 and was carried by the mudflow $1\frac{1}{2}$ km down the valley, entering at the upper left corner of the photograph.

The phenomenon of the mudflows is even more interesting. At first sight, it is difficult to understand where an adequate volume of water came from to provide the great mobility of the mass of earth, trees, and boulders. There is only one likely source for this water: within the porous pumice and scoria that made up at least 70% of the material involved. Under pressure of the downward slipping mass, water would be squeezed out from the porous fragments, and as the mass gained volume and speed the expressed water would provide additional lubrication, so that near the foot of the slope the whole mass would have the consistency of a liquid mudflow. Several such flows, coalescing in a narrow valley, would easily form a surging wave such as was observed at the time. As the main flow passed and the water drained out of the mass, the wave-like frozen billows of mud, which now remain as

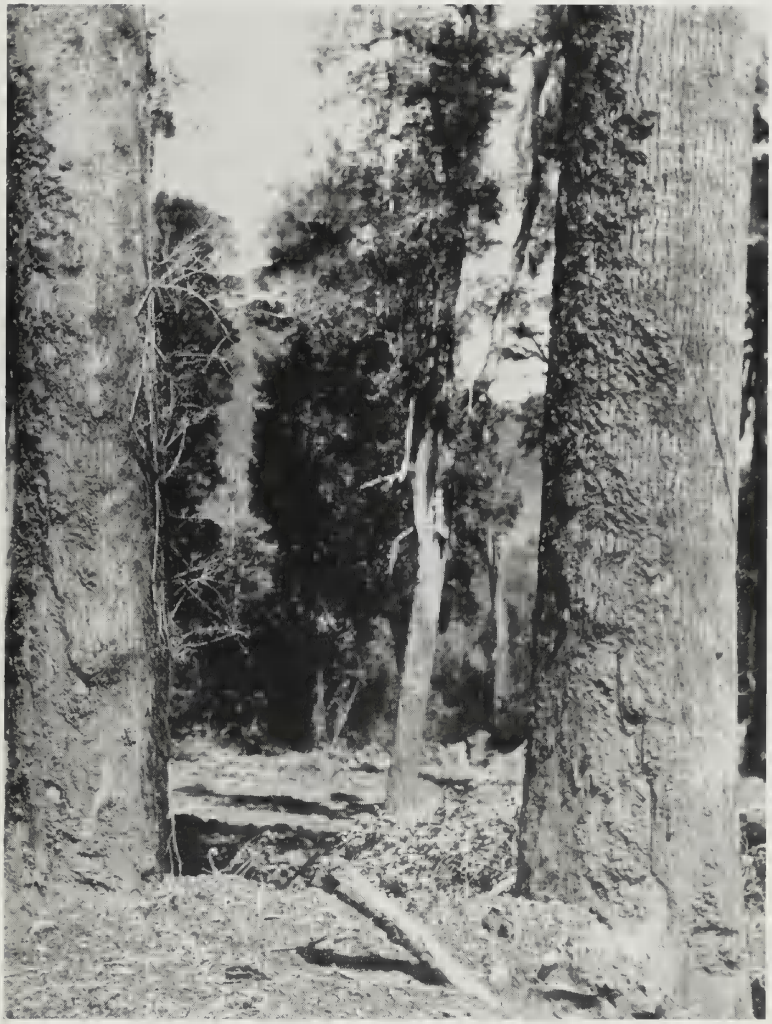

Fig. 11. Trees Near the Lakeside That Survived the Passage of a Mudflow. Note the bruised bark and mud-splattered trunks.

a characteristic feature of the landscape, would be formed. The edge of the mudflow has a characteristic upturned rolling form, solidified at the point where the water was inadequate for the journey onward into the lake. The mist that developed in conjunction with the landslips may also have been due to droplets of water forced under great pressure from the porous pumice and scoria gravel.

When the mudflows began to lose impetus as they traveled across the flat land, a few large trees managed to remain in place. The lower part of their trunks are still buried in debris, but their bark is bruised and mud-splattered (fig. 11) far above the present ground level, testifying to the passage of the wave. Observers estimated that the mudflow advanced at a speed of about 30 km/hr.

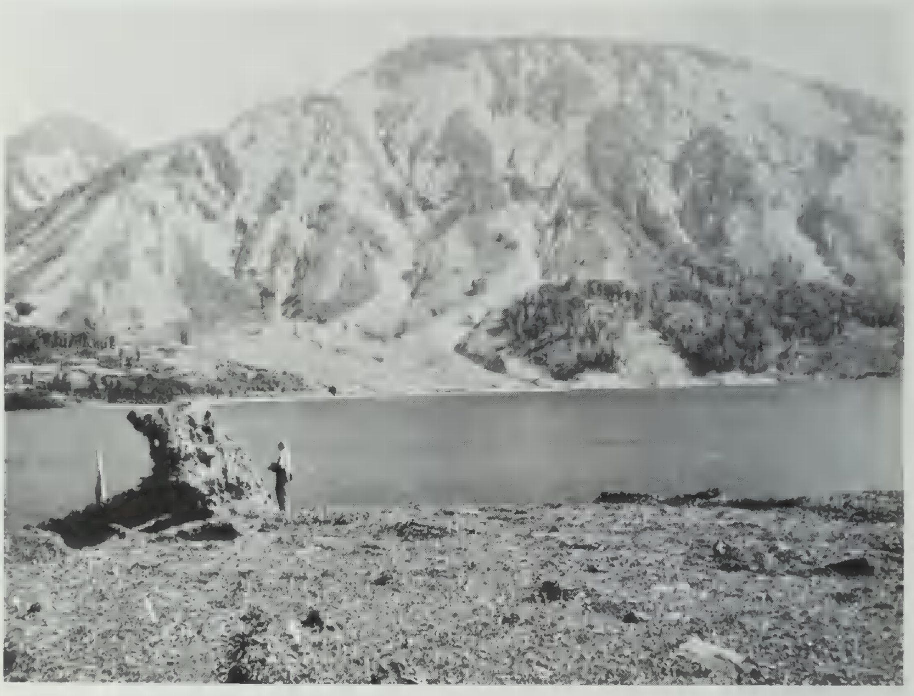

FIG. 12. The Edge of a Mudflow Where it Discharged Directly Into Lago Rupanco. Another large mudflow can be seen on the opposite side of the lake. The latter mudflow occupies the site of the destroyed agricultural settlement of Gaviota.

One feature, hitherto perhaps not fully appreciated by geologists and pedologists, was the ease with which huge slabs of rock could be floated for considerable distances. One boulder of andesite, of a size greater than 100 m^3, was observed from the time it emerged from a lateral valley to the time it reached a new resting place near the lakeshore, having traveled a distance of $1\frac{1}{2}$ km from the point of its first appearance.

Much of the debris from the disaster surged directly into the lake (fig. 12) and created a wave that extended the damage around the lakeshore far beyond the area most seriously affected by avalanches and mudflows. Narrow sandy beaches and sandspits at the mouths of streams disappeared at this time. Along other sections of the lakeshore, before the arrival of the waves, the oscillations of the ground during the earthquake caused unconsolidated materials at the edge of the lake to slide into deep water. This caused displacement of one or two houses and farm buildings before the shockwave arrived to finish the destruction.

5. *Valdivia City and Southern Valdivia.* The city of Valdivia and the coastal region to the south of the city (fig. 1) suffered severely from a number of causes.

In South-Central Chile, by far the worst affected town was Valdivia, where at least 60% of the buildings in the center of the city were destroyed or severely damaged. Valdivia is located a short distance inland from the sea at a point where the Rio San Pedro, carrying the effluent waters from a system of large inland lakes, breached the coastal range. The site is a gently undulating one, ranging from 10 to 50 ft above sea level, near the bank of the Rio Calle-Calle (the name given to the lower reaches of the Rio San Pedro) opposite its confluence with the Rio Cruces. The substrate on which many city buildings have been constructed is, in part, Recent alluvial material; in part, Quaternary sediments consisting of weathered gravels, sands, and clays; and, in the higher parts, weathered mica schist. Undulations in this terrain have been filled in with soil and other debris to form the almost level foundation of the city.

Internal packing and lateral sliding of the filled in areas, and also similar movements in the weakly consolidated alluvial sediments near the river, were responsible for most of the displacement of buildings in Valdivia (Doyel, Maraga, and Falcon, 1960). Indeed, this observation applies widely in towns throughout South-Central Chile. In some localities, even the partially weathered Quaternary gravels underwent considerable displacement, particularly when located near steeply sloping margins of rivers or lakes. In many cases, instability was clearly associated with the presence of ground water at levels near the surface; but in other cases, instability appeared to be caused by the presence of beds of weathered volcanic ash interbedded among the gravels. These ash layers have weathered to the stage in which they are rich in allophane, a type of clay that is fairly stable when dry but can absorb a very large amount of water, which is subsequently expressed when shaken under pressure, producing a remarkable phenomenon resembling liquefaction. During the earthquake, the material in these ash layers became liquefied, thus permitting the gravel beds above to fracture and blocks of the gravel to slide laterally *en masse* into gulleys, rivers, or lakes. Movements of this type were particularly noticeable in towns sited on dissected terrace landscapes composed of gravel beds interlayered with ash beds; for instance, the town of Rio Negro, where the damage to buildings was very severe.

On the other hand, the same beds (weathered gravels interbedded with volcanic ash) generally proved to be stable where they occurred in relatively poorly dissected landscapes, presumably because there was less scope for lateral movement. Younger, fresh gravels, consisting mainly of loose and rounded materials, seem to have absorbed the earth shocks more successfully. In some places (e.g., Los Pellines, on the west side of Lago Llanquihue) heavily and unevenly loaded storage barns survived with only minor damage. Beds of sand generally proved to be fairly stable as building sites if the sands were in a dry condition at the time of the earthquake; but in cases where the lower levels of the sand beds were saturated with water, quite severe damage occurred.

The newly constructed, cement-paved sections of the Pan-American, or Longitudinal, highway which follows the general route of the main north-south railroad) resisted damage fairly well, and road traffic was interrupted by the earthquake mainly because of the collapse of sections of earth-fill used to form approaches to bridges The bridges themselves usually escaped serious damage. A few short sections of road were actually thrown out of alignment, but the cause was, in almost every case, the displacement and further consolidation of filling material that was either defiicent in gravel or contained too high a proportion of clay soil with allophane. In some of the worst examples, the filling material consisted almost entirely of a type of volcano ash material that is exceedingly rich in allophane clay, a material which thus demonstrates its unsuitability for highway construction purposes. The permanent way of the railroad was seriously displaced, and rail traffic in Llanquihue Province had to be suspended for several weeks.

Flat land in the vicinity of Valdivia suffered invasion by sea water. At this writing, one year after the disaster, this land remains under water—no longer so salty as formerly, but still subject to tidal fluctuation. It is by no means certain that the submergence of this low-lying land was due solely to a general sinking of this part part of the continent. Some deep borings, made before the earthquake, showed that in the subsurface materials there were several layers of buried peat interspersed with layers of alluvial and estuarine clays. It is likely that the lowest and most decomposed organic layers suffered sudden compaction during the earth shocks, thereby causing most of the subsidence of about 1 meter 50 cm, observed on these lowlands. The nature of these underlying sediments is of some interest, for it implies that the sea has flowed in over the area on more than one occasion in the past. Reemergence of the land has apparently been brought about by estuarine sedimentation with a gradually increasing amount of river alluvium, until the water became shallow enough to allow a swamp vegetation to develop and build up a layer of organic residues, which finally raised the land above the water. In view of this history and and of the general instability of the region, it would seem more logical to try and hasten the reemergence of the land by measures to control and promote alluvial sedimentation (by a modification of the technique of "warping" such as is used in the eastern counties of England), rather than trying to seal off the area and pump out the water.

Coastal regions south of the city of Valdivia suffered great damage from tsunamis. A visit was made to the small coastal settlement of Pucatrihue 10 days after the tsunamis had passed. Here, the coast had only minimal protection sand barriers, and when the tidal wave arrived at about 3:15 on Sunday, 22 May, it swept directly over the foreshore and surged up the coastal cliff to a height of about 12 meters. The strip of flat sandy soil along the coast, nowhere more than ½ km wide, was momentarily engulfed under about 6 meters of sea water, most of which rapidly drained back into the sea. Most of this land is now covered with 6 to 30 cm of sand, but within a short time this land was again growing grass.

The wave entered the small estuary of the Rio Trufun and increased in height slightly as it moved up the narrow valley, sweeping the bushes and trees on the valley slopes to a height of about 7 meters above normal river level. Almost all the farms and holiday residences (and the local police post) within the estuary were swept up river, and the effects of the wave are clearly visible $4\frac{1}{4}$ km inland from the river mouth. White sand was deposited on valley slopes wherever the wave passed. The mouth of the river now has a new sand bar, much larger and closer to the coast than formerly. The steep slopes of the valley are mainly covered with natural forest, but none of the indigenous species seem to have been affected by their brief immersion in the mixture of sea and river water, although some trees were undermined and swept away, and in a few places landslips are blocking the only access road.

A similar sequence of events is reported from Huiecolla, (10 km up the coast from the Rio Bruero) but in this section there were very few permanent habitations. In this locality it is reported that there was a single big swell that passed over the sandy flats, surged up the cliff to more than 10 meters above mean sea level, and traveled for a considerable distance up the valley of the Huiecolla stream. No accurate bench marks are available in the area, but it is generally agreed that the sea now rises to a maximum tide level of about 1 meter 50 cm more than formerly. Certainly, even at low tide, some of the forest-covered flatland bordering the estuary at Pucatrihue is now submerged, although this could be due, in part, to the blocking of the river mouth by the sand bar in its new position.

6. *Northern Valdivia.* The largest settled area along this stretch of the coast is at Mehuin (figure 1), and, as in the case of Queule, Tolten, and Puerto Saavedra to the north, the town was swept almost entirely away by the tidal wave of Sunday, 22 May.

The earthquake in Mehuin was felt as two distinct shocks. The first and smaller was followed a few minutes later by a heavier shock that caused some structural damage. The sea was observed to recede shortly afterwards and then the tide advanced more rapidly, flooding the town to a depth of about 2 meters. By this time, most of the population were on their way to nearby high land, sitting on roofs, or perched in trees. The sea then retreated to about normal high-tide level, and then rose again and the crest of the second inundation arrived about 5 minutes after the earlier one, but flooded the town to a depth of about 7 meters. Most of the damage and loss of life was caused by this wave, which set many wooden houses adrift, and the floating debris destroyed other buildings. A third large wave followed quickly after the second, and for some time afterwards smaller surges were experienced.

On the open coast, the highest point reached by the sea was about 15 meters above the former mean sea level. The waves entered the valley of the Rio Lingue and swept inland with diminishing force for 6 km. Farm buildings on the alluvial bottom lands were flooded and many such were destroyed, along with livestock trapped in the meadows. A thin covering of sand was left on the soil wherever the wave passed. When the water became more tranquil, it was noticed that all the lower lying land (a strip 4 km long and averaging $\frac{1}{2}$ km in width) remained flooded with sea water. This area represents the more fertile part of the alluvial soils of the valley bottom land originally from 50 cm to 1 meter 80 cm above former hightide level. The sea water now occupying this part of the valley has a tidal range of about 80 cm.

The force of the wave at Mehuin seems not to have been so great as at Pucatrihue or Bahia Mansa, and the inundation took place over a longer interval of time; but since the Lingue Valley is wider and occupied by fertile alluvial soils of greater agricultural value, the damage to soil resources has consequently been greater. Agricultural damage is largely confined to the lowlands that now are permanently flooded by sea water. The soils of the margins of the valley, which were only briefly flooded by the wave and subsequently drained fairly quickly, have suffered little permanent damage although they now have a brackish water table at a depth of 20 to 40 cm. So far, their soil structure seems to be unchanged, and above the water table, worms are living normally. The thin veneer of new surface sand will make little difference to the fertility of these soils.

Considerable changes have occurred in the disposition of the sand masses in the vicinity of the river mouth, but the presence in the valley of salt tidal water indicates that the inundation is due to subsidence of the level of the land relative to that of the sea, and not primarily due to sand obstructing the outlet of river water.

7. *Central Valdivia.* The central part of the Province of Valdivia suffered slightly from minor landslips, which disrupted road communications and produced some damage on farm properties. The most seriously affected farming districts were those located among the foothills of the Andean Cordillera. The population of Liquine District, southeast of Lago Pellaifa (figure 1), was isolated for many weeks, and food supplies had to be dropped by air. The worst affected districts were those with soils composed of alternating layers of porous volcanic gravel and fine, allophane-rich ash, similar in many respects to the soils at Rupanco. The landslides took the form of massive debris avalanches, but with only minor development of mudflows, and also simple landslips caused by the collapse of steep sections of a valley wall.

The most serious of these landslips occurred in the San Pedro Valley near the egress of this river from Lago Riñihue. In this lightly populated region, no lives were lost at the time of a massive displacement of material in the cliffs along the north side of the river valley, but, as had happened 386 years earlier, the waters of Lago Riñihue (and all the water in an extensive system of intercommunicating inland lakes) were impounded behind a gigantic debris barrier, thus forming a constant threat to the people in the San Pedro Valley below and the more heavily populated Valdivian lowlands. The valley wall collapsed in three places, and the blockage was thus in three sections, that furthest downstream being the largest and nearly a mile in length. After an initial survey to establish levels, engineers labored valiantly (through 2 months of atrocious wet weather that augmented the water impounded in the lake until it reached to over 35 feet above normal level), digging through the debris in order to release the impounded water under some sort of control. At the end of July 1960, this task was completed. As a precautionary measure, population and livestock were evacuated from low-lying parts of the San Pedro Valley and from the lower sectors of the city of Valdivia before discharge of the water began. During the discharging process, severe flooding occurred in these lowlands, but the amount of silt left behind when the waters receded was comparitively small. In the upper reaches of the valley, almost no material was deposited. Deposition of silt and sand was probably very heavy during the first three days of the discharging period (the stage when the earth barrier was crumbling), but, during the last three days, the swollen river was charged mainly with lake water, almost free of sediment, and the speed of the current was such that much of the sediment deposited earlier was swept away. Indeed, during the final phase, considerable erosion of the river bed occurred and former islands in the river disappeared. Farmers in the valley suffered more from erosion and from destruction of fences and outbuildings than from heavy deposition of alluvium.

The cause of the giant Riñihue landslips is not known for certain, but it is noteworthy that the thick beds of glacial outwash, which here are mainly sands and gravels, also contain layers of volcanic ash, weathered to the stage where they are rich in allophane clays. Thus, one of the same elements of instability is present here as was found in the case of the major landslip areas of the cordillera.

8. *Pellaifa.* Extensive landslides occurred on the steep slopes bordering the head of Lago Calafquen and on the whole of the steep land around Lago Pellaifa (figures 1 and 1e). These landslides completely severed the road passing along the north of Lago Pellaifa, resulting in the isolation of farming communities in the valley of of the Rio Llizan—a district usually referred to as Liquine. Between 3,000 and 4,000 persons (including those isolated as a result of the Pellaifa landslide and those of of the Liquine district) had to be supplied by air for several weeks. Part of the debris from the landslips fell across the effluent stream connecting Lagos Pellaifa and Calafquen, and the water of Lago Pellaifa stood some 5 meters higher than formerly, so that many portions of the former road around the lake, if not actually buried in landslide debris, were under several meters of water for about 2 months. The job of reopening this road involved not only removal of landslip debris, but also the clearing of debris from the lake effluent. About 80 persons actually perished in in the area affected by the landslides, and most of these were small farmers—some being indigenous Indian (Araucarian) families.

As in the case of the debris avalanches at the head of Lago Rupanco, the Pellaifa landslips occurred on slopes mantled with coarse, porous volcanic ash. At Pellaifa, the underlying rocks are more varied than at Rupanco and include sedimentary rocks, granitic rocks, and acid volcanic rocks in addition to andesite and basalt. The ash mantle is thinner than at Rupanco and is composed almost entirely of fine and coarse pumice erupted long ago by Volcan Villarrica. This pumice forms almost the entire subsoil; the topsoil is formed from more Recent fine sand and very fine pumice, also probably originating mainly from Volcan Villarrica.

Originally, the slopes of the hills bordering the southern side of the head of Lago Calafquen and both sides of Lago Pellaifa were forest-covered. The flatland between the village of Conaripe and the western end of Lago Pellaifa has been settled for many years. At first, the settlers were engaged in exploiting timber, but as the lowland became gradually cleared, farming developed on the flatland and on the lower slopes of the hills. Two large agricultural estates (Culan and Aniques) and five indigenous farm settlements (Reductos Llancatillo, Cafrilat, Antimilla, Lemonas, and Antiques) were affected by the landslides. Cleared land is used mainly to provide grazing for livestock, and only very small areas are plowed and sown in wheat. Timber extraction is still the main source of income for the local settlers.

and farming is carried on mainly to provide for the subsistence of the local population.

During the three consecutive very dry summers of 1942, 1943, and 1944, several forest fires occurred in the district, and one big fire (originating near Curacautin) swept through most of the upland cordillera forests. On the lower and middle parts of the steep hillside, much of the original forest has been replaced by fern wasteland. This covering of fern is burned, in part, almost every year by fires that spread from land-clearing operations on the flat and rolling land at the foot of the slopes.

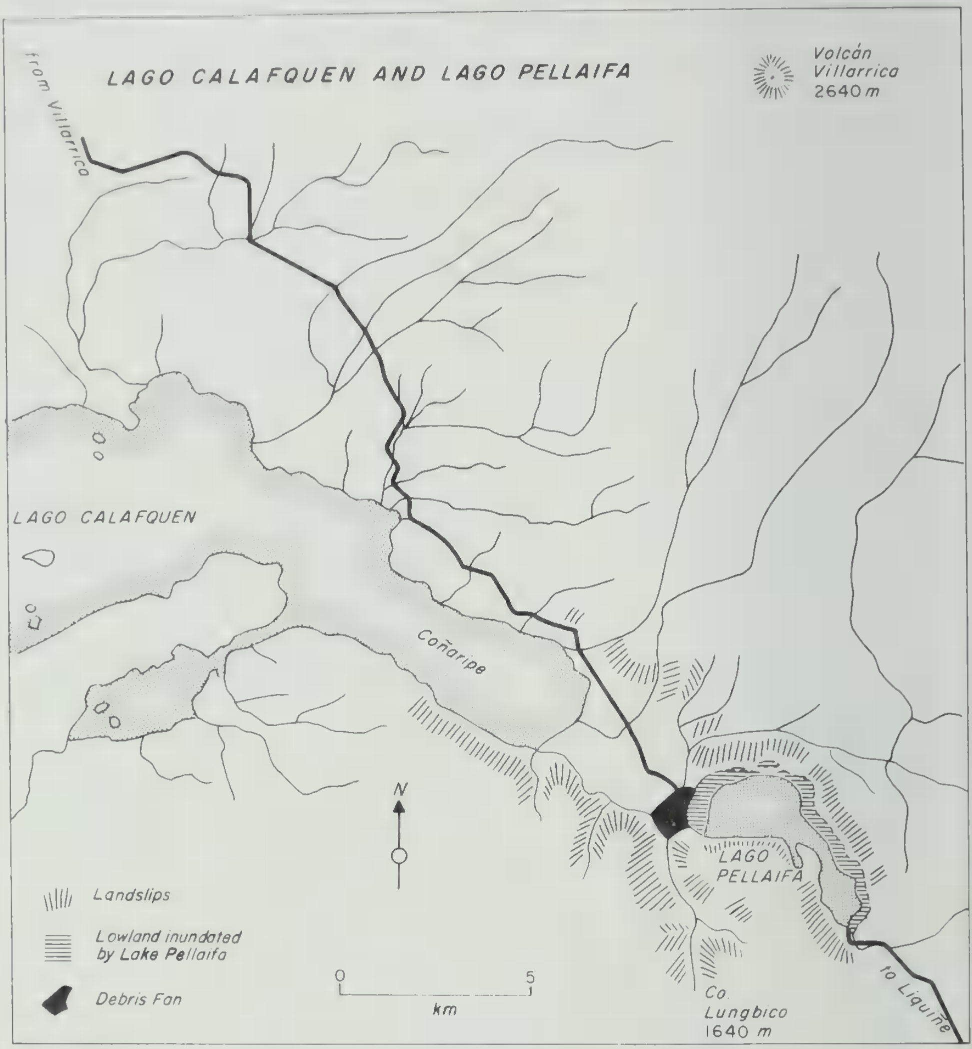

FIG. 1 (e). Landslips and Inundated Areas in the Lago Calafquen and Lago Pellaifa Section.

As in the case of the debris avalanches of Lago Rupanco, the steep slopes occupied by grass and fern slipped away, almost totally. Steep slopes occupied by burned-over forest were slightly more stable, but here, too, in many cases, the plant and soil mantle slipped away completely, over a whole mountain face, leaving only a few forested ridges (where Coigue trees are dominant) still in place. Of the less disturbed forest at higher levels a good part still remains, but this upper area is badly scarred by the path of debris avalanches, which developed mainly along the stream pattern. The pattern of erosion from the steep slopes is therefore different and more varied than at Rupanco, but, in contrast, the Rupanco-type mudflow failed to develop.

The reason for the absence of mudflows may be that the soils in the Calafquen-Pellaifa area are composed of a smaller proportion of porous, water-holding material and, at the time of the earthquake, they were in a much drier condition than those at Rupanco. In the Calafquen-Pellaifa region, there had been a very dry spring, a normally dry summer, and a fairly dry autumn; moreover, the only period of heavy rain occurred during one week in March. The week preceding the earthquake had been without rain. During very wet autumns and winters (i.e., as in 1959), small landslides are a normal feature of the deforested slopes in the region.

As in the case of Rupanco, the valley became filled with a fine mist immediately following the landslides, but the amount of water pressed out of the pumice seems to have been insufficient to lubricate the mass of debris and convert it into a mudflow. The only exception seen was in the case of the debris that accumulated in the narrow valley of the stream draining directly from Lungaico Peak. This valley filled completely with debris from landslides for a distance of some 4 km, and the whole mass was ejected as a spate of debris, entering the main valley near the point of origin of the stream joining Lagos Pellaifa and Calafquen. The mass flowed out from the side valley, across the effluent stream from Lago Pellaifa, and, reaching the opposite wall of the valley, formed a debris dam 4 to 5 meters high at the lowest point. This barrier now partially contained the waters of Lago Pellaifa, and a new outlet has developed at the northern end of the barrier. However, this feature seems to be unique in the area—most of the landslides merely accumulated as a rubble at the foot of the slopes or plunged directly into either of the two lakes. The total area affected was about 11 km long by 3 km wide.

Landslide areas of smaller extent are reported further inland from the valley of the Rio Tranquil and the slopes below the upland Lago Calafquen, which lies to the east of Liquine. Landslides are also reported from the vicinity of Millahuehuin in the Trancura Valley, southeast of Pucon. The steep land soils in this area, like those of Pellaifa, consist of pumice layers on very steep slopes that become unstable if the natural forest cover is molested.

On both Lago Pellaifa and the upper end of Lago Calafquen, a large wave swept the shoreline almost simultaneously with the descent of the landslides, and for some time afterwards smaller secondary waves ricocheted back and forth across the lakes.

9. *Arauco.* The coastline between Lebu (in the Province of Arauco) and Dichato (in the Province of Concepcion) (fig. 1) rose between 75 cm and 1 meter 80 cm

during the first seismic activity on 21 May (Galli and Sanchez, 1960). No subsequent uplifting or depression occurred during the earthquake on the following day. A brief visit was made to this part of the coastline soon after the earthquake, but because of heavy rain all the lowland areas were partially inundated and little of interest could be observed. Some of the headlands showed that mussel beds were now exposed to the air except during the highest phases of the tides, and it seemed beyond question that some coastal uplift had taken place.

A much more prolonged visit was made to the area in the following December and January (1961), and ample confirmation of an uplifting was obtained, both from the condition of wave-cut platforms on the headlands and from the lowland soils in embayed sections of the coastline. Not only were many of the wave-cut ledges now accessible only to very high storm waves, but, in many rocky sectors of the coast, slightly elevated boulder beaches were in the process of being wave-cut to a new base level. In general, the amount of elevation was insufficient to put former beach materials out of reach of the largest waves, and all the recently elevated deposits of drift materials were in the process of undergoing intermittent resorting; some were gradually being swept entirely back into the sea. There was, as a consequence, no really good site for the study of soil formation in coastal drift materials. Examination of several areas of swampy flatland along less rocky sectors of the coastline provided undisputable evidence that the mean water-table level had been lowered; soils that formerly were subject to strong reducing conditions in all horizons now showed a deep surface zone where oxidation had begun and had been consistently in progress for some time. In this horizon, the normal gray colors were on the wane and the pattern of mottling was changing. It is thus possible that for many of these potentially valuable flatlands drainage schemes could now be devised; formerly they were regarded as being too expensive to drain owing to their proximity to mean sea level.

Damage to Soil Resources

Damage to the soil resources of South-Central Chile resulting from the seismic disturbance of May and June 1960 is thus of several types and has resulted in the total loss of some soils, partial destruction or severe modification of other soils, and minor modification of a third group of soils.

Soil Resources Totally Destroyed: These include lowland soils of the coastal region from Tolten southward, which are now permanently inundated by sea water. Most of these soils are considered as being totally lost to agriculture because the cost of poldering and maintaining an efficient mechanical drainage system, even for small areas, will almost certainly exceed the return obtainable from agricultural production on the reclaimed soils. There is also the strong likelihood that, from time to time, in the distant future, further seismic movements will occur. Schemes for controlled flooding to accelerate and localize the build-up of alluvial sediments may be applicable over part of the inundated area, but there is little in the way of a general scheme that can be suggested for the whole affected region; certain areas might eventually have to be employed for fish and frog production. As part of the natural soil resources of Chile, most of these soils will almost certainly have to be considered a total loss. The total area involved is about 40,000 hectares.

The regions most affected by inundation of this type extend southward along the coast from Tolten to Puerto Montt, mainly pockets of flatland between the coastal dunes and the foothills of the coastal range, and the alluvial land bordering rivers, where they approach the coast. A high proportion of fertile alluvial soils are involved. On about 30% (12,000 hectares) of these, agricultural development had achieved a comparatively advanced level through milk production and the growing of market garden crops, potatoes, and root crops. About 50% (20,000 hectares) of the drowned farmland was in an earlier stage of agricultural development, where, because of insufficient capital, access difficulties, land-tenure problems, or other problems, farmers had not yet achieved a high level of production. About 20% of the drowned land (8,000 hectares) was occupied by natural forest or second-growth vegetation at the time of inundation, but probably less than half of this category represents soils of good potential quality that might one day have been developed for agriculture.

A different class of soil, which was totally destroyed during the seismic disturbances, consisted almost entirely of steep land soils that plunged, in the form of landslides, debris avalanches, and mudflows, directly into the depths of various lakes. The total area involved is probably in the neighborhood of 20,000 hectares. Practically none of this land was well adapted to agriculture, although about 10% (2,000 hectares) of the lower slopes had been partly cleared by farmers living along the lake margin, in an effort to provide additional grazing for the livestock on their small farms. In their downward plunge into the lake, the debris avalanches and mudflows destroyed some 700 hectares of better-class farmland and about 200 people from the various farming communities.

Two main regions were involved: the upper (eastern) end of Lago Rupanco in the Province of Osorno; and Lago Pellaifa, with part of the upper (southeastern) end of Lago Calafquen in the Province of Valdivia. The Osorno debris avalanches cover about one and a half times the area of those in Valdivia, and were far more impressive in that, in many cases, the face of the whole mountainside was stripped clean of vegetation and soil. Individual avalanche areas have measured up to 800 hectares in area. Whereas the debris avalanches of Rupanco cleared whole mountainsides, those of Pellaifa and Calafquen were more of the character of landslides, less well lubricated, confined to narrower paths, and they did not give rise to mudflows in their terminal phase. Both regions had in common a history of periodic forest fires.

The loss of these national soil resources is, therefore, not unconnected with past land-use policy, which has permitted the development of farm settlements in proximity of slopes carrying a type of soil that is highly unstable even under natural conditions. Such areas should be reserved for forest development or developed for carefully selected grazing areas under very carefully controlled management.

In all, some 60,000 hectares of the natural soil resources of Chile have been completely lost; but of this total, probably only 36,700 hectares represents soils of real, or potential, agricultural value (see table 1).

Soil Resources Partly Destroyed: This includes soils transported (but not irrevocably lost) through landslides, slumping, mudflows or other forms of mass movement and also includes some lowland soils immediately adacent to land inundated permanently by the sea. These latter soils were formerly well drained. In some cases, the new ground-water level is dangerously close to the surface of the soil (i.e., at depths of less than 30 cm).

The main areas where widespread transportation of soil occurred are Rupanco, Calafquen, Pellaifa, and Panguipulli; but small isolated examples occurred in the Trancura Valley and in the Tranquil and Liquine districts. All are in the precordillera or cordillera zone and all involve steep land soils that are pumiceous or scoriaceous in composition or are derived from ash minerals which, at one stage

TABLE 1

APPROXIMATE AREAS OF SOILS LOST OR MODIFIED AS A RESULT OF SEISMIC AND ASSOCIATED DISTURBANCES OF MAY–JUNE 1960

Soil condition	Total area affected, hectares	Portion of total area affected suited to agricultural production, hectares
Totally Destroyed		
Permanent inundation by sea water		
In advanced stage of agricultural development	12,000	12,000
In process of agricultural development	20,000	20,000
Undeveloped	8,000	4,000
Plunged into deep lake water		
Mainly steep land soils unsuited to agriculture, but total includes some partially developed hill soils	20,000	700
Total	60,000	36,700
Partially Destroyed or Considerably Modified		
By landslides, debris avalanches, slumping, etc	15,000	1,500
By mudflows	500	400
By development of saline water-table surface	1,500	1,200
Total	17,000	3,100
Slightly Modified		
By salinization during temporary immersion in sea water	23,000	11,500
By addition of veneer of coastal sand	800	700
By addition of pumiceous volcanic ash		
between 1 and 5 cm deep	35,000	18,000
more than 5 cm deep	22,000	3,000
By permanent rise in level of ground water	17,000	10,000
By temporary flooding by lake waters	13,000	8,000
By minor displacement (slumping, minor slips)	3,000	900
Total	113,800	52,100

of weathering, form a high concentration of allophane clays. The latter, when dry, have properties akin to fine sand, but when wet they become exceedingly slippery. The combined effect of heavy rain following a very dry summer, repeated disturbance of the natural plant cover by burning and grazing, and finally the severe earthshocks, were the main factors responsible for the widespread landslides. At least 15,000 hectares of steep land soils were dislodged and transported rapidly to a new location on the valley floors at the foot of the slopes, where they now form a rumpled heap of soil and forest debris of far lower agricultural value, for the moment, than the original valley soils that they overwhelmed. In some places, the debris is spread out more evenly and in time may rapidly be developed into useful farmland. Some of the area damaged by this type of transportation was of little real agricultural value formerly, but of the total area involved, some 10% (or 1,500 hectares) represents useful agricultural land now buried under debris.

Where mudflows developed (such as those at Gaviota at the head of Lago Rupanco) almost all the destroyed land was agriculturally valuable. Of the total of 500 hectares devastated by mudflows, some 400 hectares represent land that was formerly producing meat or subsistence crops for the farming community. The new soils of the mudflows are mixed with about 40% (by volume) of forest debris, but they are already fairly well consolidated; successful efforts were made in some cases to resow them with grass and clover seed while the surface was still free from weeds. Owing to the protruding forest debris, the soils are too difficult to work with machinery, and the only alternative to the costly method of sowing by hand would have been to seed them by airplane. Unfortunately, no suitably equipped plane was available. The soils are fertile and only very slightly acid in reaction. Gaviota was formerly the site of a farm-colonization scheme, but so widespread has been the destruction of the soil resources in this area that it would now be more logical to transfer the survivors of this colonia to a more favorable and less perilous location.

The soils that have acquired a saline water table near the surface are to be found in many of the narrow coastal valleys, and, in some cases, extend as far inland as 5 km from the coast (e.g., in the Lenga Valley near Mehuin). They occur usually in narrow strips or in depressed areas close to the inundated area, but the total area may amount to as much as 1,500 hectares. Of this total, probably 1,200 hectares represent land normally used for cereals, potatoes, root crops, or dairy pastures. In the case of sandy soils, salt may be expected to concentrate in the topsoil during dry summer conditions and cause the loss of part of the crop. In the case of heavier soils (clay and clay loams), some additional loss of structure and deterioration of aeration may be expected. The total area of soils partly destroyed, or radically modified, as described above, amounts to about 17,000 hectares, of which some 3,100 hectares represent land formerly well adapted for agricultural production.

Soil Resources Slightly Modified: This includes the soils that were briefly immersed in sea water during the abnormal tidal surge that followed the earthquake of 22 May; soils that received a thin veneer of dune sand carried inland by the tide soils that received a top-dressing of volcanic ash during the eruptions from Volcan Puyehue; soils that have suffered deterioration of drainage owing to the rise of the water table (possibly permanent in the case of areas with general depression of the land surface but temporary in the case of some lakeside soils); and soils displaced by minor slumping or slipping.

Of the soils temporarily or briefly inundated by sea water, some 23,000 hectares were affected, and about 800 hectares were found to have a thin surface layer of sand when the water receded. Of the total area washed by sea water, some 11,500 hectares represented valuable agricultural land; practically all the land receiving extra sand also belongs in this class. However, there is no evidence that these soils have seriously deteriorated after their brief (usually only a few hours duration) immersion. When the soils of Puerto Saavedra and Tolten were examined early in June 1960, the measurable salt content of the sandy and other light textured soils was already almost back to normal; while in the case of the clay and clay-loam soils, salinity was only slightly above normal. By the end of August 1961, all the affected soils returned to their normal salt content. Earthworms, larvae of insects, and other important soil organisms appeared to remain alive and vigorously active despite the flooding with sea water, and grasses soon put forth new shoots. Of the pasture plants, only some of the legumes suffered. In parts unprotected by a close vegetation cover (for example, fields with potato and sugar beet crops), there was considerable erosion of surface soil, but this soil material was usually transported only short distances across the flat plain.

A modification of a slightly different type was experienced by the soils near Lago Puyehue in Osorno Province, where the eruptions from Volcan Puyehue provided a dusting of pumiceous sand over a wide area. During the period of the most violent eruption (24 to 29 May), the wind blew consistently from the west, and most of the volcanic ash was deposited over the central Andean Cordillera or fell in Argentina. At Osorno, less than 2 mm accumulated over a 10-day period, and a similar amount was recorded at Rupanco. A faint film of fine ash could be found as far west as Pucatrihue during the eruption, but even at Termas Puyehue, only 15 km from the seat of the eruption, a total depth of just over 1 cm was recorded during the most active period of eruption. In the lower part of the Golgol Valley, the depth of fresh pumice sand varies between 1 and 5 cm and includes some larger fragments of fusiform pumice gravel. Rain fell intermittently during the most active phase of the eruption, and, as a result, most of this ash in the lower valley was resorted and dispersed by flotation. At the upper end of the Golgol Valley, within 10 km of the vent, the new material is mainly pumice gravel and is generally more than 5 cm in depth.

The total area in Chile receiving pumice sand and gravel from the eruption to a depth of over 5 cm was about 22,000 hectares, but of this, less than 3,000 hectares represent land of gentle relief suited to agricultural production. Beyond this central zone extends a wide area of soils that received from 1 to 5 cm mainly of fine pumice sand. The total area affected is in the region of 35,000 hectares, and, of this area, some 18,000 hectares represent land actually used for agricultural production.

Samples of the fine and coarse material were collected and analyzed. They appear to be of a remarkably pure siliceous type of ash, which will probably make little if any significant difference to either the fertility, structure, or water-holding capacity of the soils of the region.

The sinking of the land south of Tolten, in the coastal region, will unquestionably increase drainage problems over some 17,000 hectares; and, of this total, at least 10,000 hectares are land that is currently contributing to the national total of agricultural production. The magnitude of the potential drainage problems varies from place to place and with different kinds of soil, but, in general, all can be expected to flood more readily, and flood water will be more difficult to remove than formerly. There may be a gradual deterioration in subsoil aeration during the ensuing farming year; cereal crops sown before May suffered a marked decrease in yield.

In a somewhat different class are certain lakeside soils in the Riñihue, Panguipulli, and Calafquen region, which suffered temporary inundation caused by the blocking of the outlet of the Lago Riñihue by the slumping of the valley walls along the upper reaches of the Rio San Pedro. There is a similar, but much smaller, area of temporarily inundated alluvial soil around Lago Pellaifa, whose waters were also impounded behind a mass of fan debris discharged from a lateral valley, blocking the effluent stream draining Lago Pellaifa into Lago Calafquen. These temporarily flooded soils have suffered no serious damage. Lake levels have not quite returned to normal, and a very small part of this inundated soil has been lost to agriculture. At their greatest extent, some 13,000 hectares were under water, of which at least 8,000 hectares represented land in agricultural production.

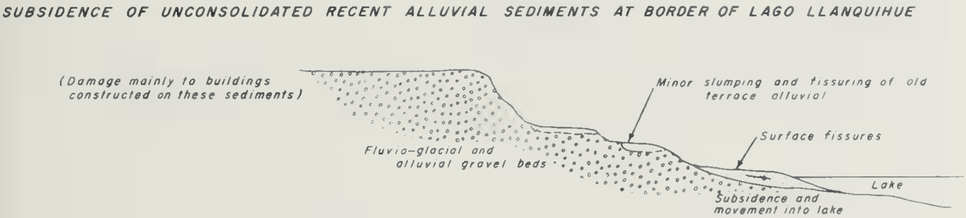
SUBSIDENCE OF UNCONSOLIDATED RECENT ALLUVIAL SEDIMENTS AT BORDER OF LAGO LLANQUIHUE
(Damage mainly to buildings constructed on these sediments)
Minor slumping and fissuring of old terrace alluvial
Surface fissures
Fluvio-glacial and alluvial gravel beds
Lake
Subsidence and movement into lake

FIG. 1 (f). Alluvial Sediments at the Border of Lago Llanquihue.

Minor displacement of soil resulting from slumping and slipping has occurred at many points around Lagos Llanquihue (figure 1f), Rupanco, Calafquen, and Ranco, and also near terrace margins in the Villarrica and Collipulli-Angol regions, farther north. The soils were not seriously displaced and probably a total of not more than 1,300 hectares was so affected, about 900 of which represent valuable productive agricultural land.

To this list of slightly modified soils should be added some of the alluvial bottomland of the San Pedro and Calle-Calle valleys. The release of the water impounded in Lago Riñihue produced two kinds of change in these valley soils. Those of the upper reaches at first received a thick deposit of fresh alluvium, but as the earth barrier crumbled and an increasing volume of sediment-free lake water poured down the valley, the initial period of sedimentation was followed by a period of scouring, which removed most of the new alluvium and further destroyed some of the original alluvial soils in the valley bottom. Lower down the valley, in that part known as the Calle-Calle section, almost all the alluvial soils received a deposit of fresh silty to fine sandy alluvium, ranging from 3 to 25 cm in thickness. Because measures had been taken to bring about the release of the impounded waters under control, remarkably little damage was done. Only about 500 hectares of the original valley soils were severely scoured; an additional 700 hectares received a top-dressing of stony and gravelly material scooped out of the former river bed; while some 1,500 hectares received a varying depth of fresh fine alluvium. The farmers who heeded the advice to sow the new alluvium immediately in clovers and grasses readily established excellent pastures and secured heavy yields of forage during the ensuing years. Established orchards (mainly apple and pear) were not seriously affected by the layer of new alluvium.

Recent Modification to the Soil Pattern: The new features of the soil pattern of South-Central Chile fit readily into the Chilean soil assemblage, thus testifying, in some measure, to the consistent nature of seismic activity in this part of the South American continent.

Modifications in the soil, caused by improved drainage that is occasioned by continental uplift, are evident along the coast from Tolten northward. It is precisely from this latitude northward that young soils on coastal terraces appear in the Chilean soil assemblage. On this particular occasion, the amount of uplift was slight, and few of the elevated drift deposits rose clear out of reach of the sea. On former occasions of seismic activity, much greater elevation has occurred in a single earth-shock, uplifting portions of the coastal shelf with its layer of coastal drift detritus into a new position where soil can begin to form (Fitzroy, 1836). Darwin (1837) records, "At Valparaiso, although in the 220 years before our visit the elevation cannot have exceeded nineteen feet, yet subsequently to 1817 there has been a rise, partly insensible and partly by a start during the shock of 1822, of ten or eleven feet." (The maximum elevation recorded in 1960 reached to 9 feet, on the island of Guafo, southwest of Chiloé.) The further north one travels in Chile, the greater the altitudinal interval between successive coastal terraces: in the vicinity of Tongoy (300 km north of Valparaiso), in the Province of Coquimbo, there is evidence of one abrupt uplift amounting to about 150 feet with remains of current marine organisms still easily identifiable in the terrace soils.

By contrast, all the evidence for drowning of landscape occurs from Tolten southward. In the Recent activity, this was in part due to the same process of continental depression that has produced the conspicuously "drowned coastline" of southern Chile, and, in part, due to consolidation of weak sub-strata rich in organic residues. In many cases, these organic residues are the product of former swamps, more or less identical with the swamp accumulations of the coastal lowland of the present time. They are to be expected to occur under cool, humid climatic conditions wherever vegetation establishes itself in areas of high water table. The fact that many of these strata are overlaid directly by layers of estuarine or marine clays implies that subsidence has been in progress for a considerable time. The return of vegetation to such areas may be explained by a small recovery in the continental position, but in many cases is clearly due to gradual building up of alluvial sediment in the area. There is little doubt that the soil changes observable in the Valdivia region during the recent seismic period are but a part of a long-continued landscape building process.

With regard to landslips and the gravitational transportation of soil and soil-parent materials, the events of May 1960 make more certain the explanation of several unusual landforms found in the Chilean lakes region. There is one kind of slumped, hummocky type of landscape, dotted with large angular boulders, often found near the head of the larger lakes. This has more than once been ascribed to a late phase of glacial activity. It is now apparent that this is a landform created by catastrophic mudflows in this region. The positioning of huge boulders in a landscape can apparently be achieved by mudflows as readily as by ice. Likewise many chaotic soil patterns of the piedmont areas are now explicable as being the product of ancient debris avalanches.

Even the damming and subsequent release of impounded water from Lago Riñihue has a historical parallel in the very same area. As recorded by Captain don Pedro Marino in *Cronica del Reino de Chile*, the embryo city of Valdivia suffered from earthquakes and tidal waves on 16 December, 1575. Four months afterwards, in April, 1576, the population were surprised by a sudden inundation coming from upstream in the San Pedro Valley. Subsequent investigation showed that Lago Riñihue had been blocked by a huge landslip near its mouth, the remnants of which can be seen to this day and are located only a little distance downstream from the side of the landslip of May, 1960.

Of the other types of changes in the soil pattern (those of a more temporary nature) little trace now remains of changes that occurred during previous cycles of seismic activity. However, with knowledge gained from recent events, we can assess more accurately the type of change that is likely to have occurred in certain soils during their formation, and this, in turn, may help to explain certain anomalous features of the existing soil profiles.

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LANDSLIDES AT LAGO RIÑIHUE, CHILE

By Stanley N. Davis and Juan Karzulovíc K.

ABSTRACT

Strong earthquakes of 22 May 1960 produced three large landslides which blocked the outlet of Lago Riñihue, 65 kilometers east of the city of Valdivia, Chile. The lake level rose 26.5 meters before water began discharging through artificially constructed canals during the last week in June, 1960. The largest landslide involved about 30 million cubic meters of unconsolidated sediments, the intermediate landslide about 6 million cubic meters, and the smallest landslide about 2 million cubic meters.

The surface of rupture of the largest landslide is within an 80-meter sequence of Pleistocene lake clays. The clays are underlain by till and overlain by outwash sands and gravels. Movement of the landslide is interpreted as having been principally block gliding and lateral spreading. Secondary landslides within the larger landslide were produced by rotational slumping, debris falls, and earth flows.

Several ancient landslides exist in the vicinity of Lago Riñihue, the largest involving more than 100 million cubic meters of unconsolidated sediments. Many of the older landslides also were probably triggered by earthquakes.

Introduction

Lago Riñihue is in the heart of the picturesque Chilean Lake District, 67 kilometers east of Valdivia, Chile (figure 1). Water in the lake comes from a large drainage basin, which extends to the Argentine border and includes many small lakes, as well as two large lakes about the size of Riñihue. The water discharges through Río San Pedro at the western tip of Riñihue. The river first flows for 6 kilometers in a valley about 100 meters deep and 800 meters wide; then it passes through a narrow canyon for 7 kilometers and eventually joins with Río Quinchilca to form Río Calle Calle, which discharges into the Pacific Ocean west of Valdivia.

The first few kilometers of Río San Pedro were blocked in three places by large landslides (figure 2), which were triggered by the strong earthquakes of 22 May 1960. The river remained blocked for 63 days, during which time the lake level rose 26.5 meters above its normal level. The total volume of water stored behind the landslides reached a maximum of about 2.5 billion cubic meters. Artificial channels were excavated to attempt a partial control of the discharge of the water. In addition, a dam was hastily constructed below the largest landslide, which is also the farthest downstream of the three landslides. Initial overflow rapidly increased, over a period of less than 2 days, to a maximum of 7,500 cubic meters per second. One week later, the discharge had diminished to 1,500 cubic meters per second. Six months later, the discharge was only a few hundred cubic meters per second, and the lake had returned to within 1 meter, or less, of its former level. Control measures in the landslide area, together with evacuation of low-lying areas downstream, prevented loss of life and minimized property damage.

Early historical records of Valdivia describe an earthquake of unusual magnitude on 16 December 1575 (Davis and Karzulovíc, 1961). At the same time, Lago Riñihue was blocked by an enormous landslide, which was not breached by overflowing waters for a period of 134 days (or until the end of April of the following year). The rapid cutting of the natural dam caused a catastrophic flood which destroyed a large part of Valdivia. Thus, the events of 1575–76 appear to have been duplicated almost 400 years later, but fortunately the recent flood was not so disastrous.

The landslides at Lago Riñihue have been visited by a large number of geographers, geologists, and engineers, many of whom have written accounts of the landslides (Weischet, 1960). A detailed engineering study of the largest landslide has been undertaken by the national electric power commission of Chile, Empresa Nacional de Electricidad S.A. (ENDESA). As yet, their final report has not been completed. The present paper is in part a condensation of a longer report in Spanish (Davis and Karzulovíc, 1961) and is based on geologic field work by the authors during February 1961, supplemented by preliminary engineering data of ENDESA.

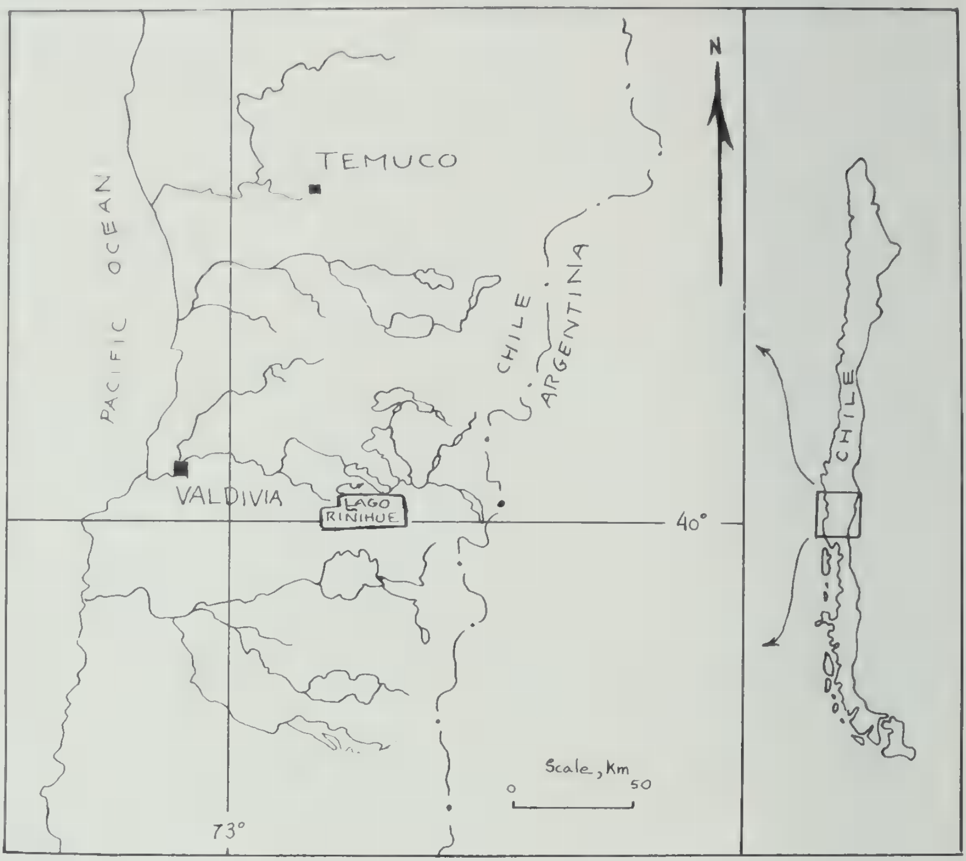


FIG. 1. Index Map of South Central Chile Showing the Location of Lago Riñihue.

Terminology used in this paper is essentially that proposed by Varnes (1958). The following two exceptions are made: (1) cracks on the original surface upslope from the main scarp are called "crown cracks," and (2) the term "unit" is applied to a given part of the landslide having a similar structure. Individual masses that may be fractured but have not been separated during movement are called "blocks," rather than units. This is only a slight extension of current usage in sedimentation, in which the term "block" is applied to very large angular clasts. Furthermore, Varnes uses the term "block gliding," so it is more consistent to call the displaced objects blocks, rather than units.

STRATIGRAPHY

The best geologic exposures are in the vicinity of the largest landslide; hence, the following discussion emphasizes the local stratigraphy of this area (figure 3). The stratigraphic succession, however, is almost identical in the vicinity of the other two slides.

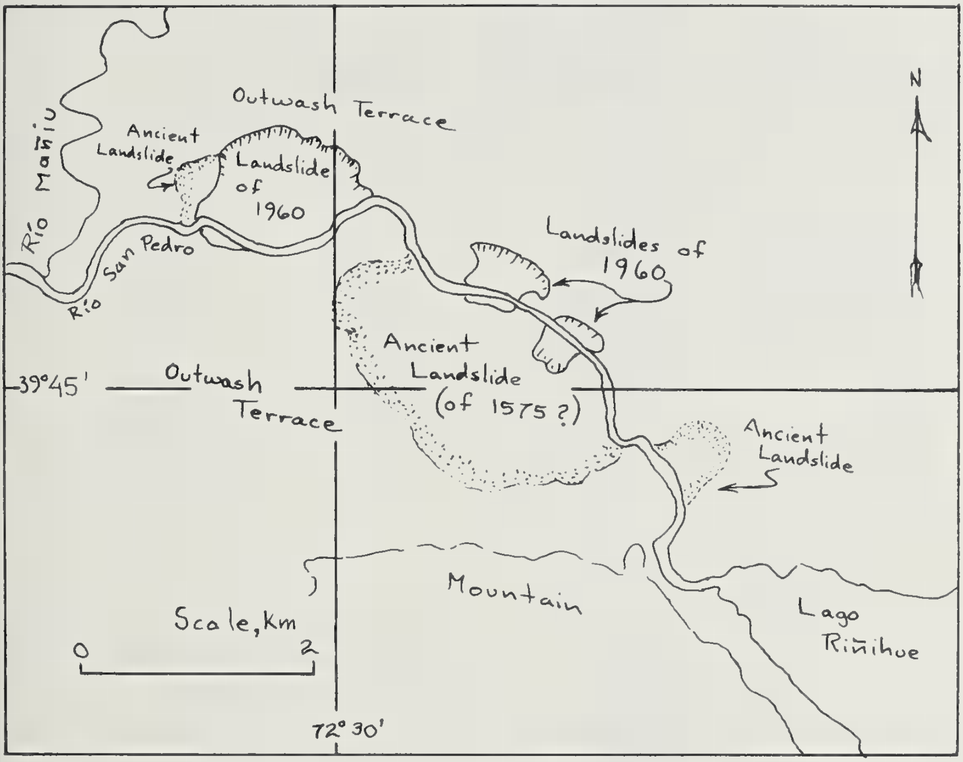


FIG. 2. Sketch Map of Three Modern and Three Ancient Landslides Which Have Blocked the Outlet to Lago Riñihue. Position of Río San Pedro during early 1961 is shown.

Highly contorted schists and phyllites are the oldest rocks (Paleozoic ?) in the landslide area. These rocks are exposed in the canyon directly west of the largest landslide. Here, the metamorphic rocks are overlain by about 15 meters of compact glacial till. An ENDESA test hole, located about 800 meters east of the outcrop and at the toe of the landslide, encountered what is probably the same till, 34 meters below the level of Río San Pedro. The hole did not reach the metamorphic rocks. Neither the till nor the metamorphic rocks was involved in the landslide movement.

In the same hole, 35 meters of lake silts and clays were encountered above the till. This thickness, combined with 30 meters exposed in outcrops and an estimated 15 meters hidden by landslide debris, indicates a total thickness of about 80 meters of unconsolidated lake sediments. The bottom part of the lake deposit consists of silts and clays; the central part, of silts and volcanic ash, with abundant plant leaves and vivianite nodules; and the top part, of alternating silt and silty clay layers which resemble thick varves. Individual beds range in thickness from about 2 to 60 centimeters and extend laterally for several hundred meters. The coarser material varies from 95% volcanic glass shards in the upper and central parts to only 5% in some of the lower silt layers. Quartz, feldspar, augite, and other less abundant minerals are dominant in the coarser grains of the lower part of the lake sediments.

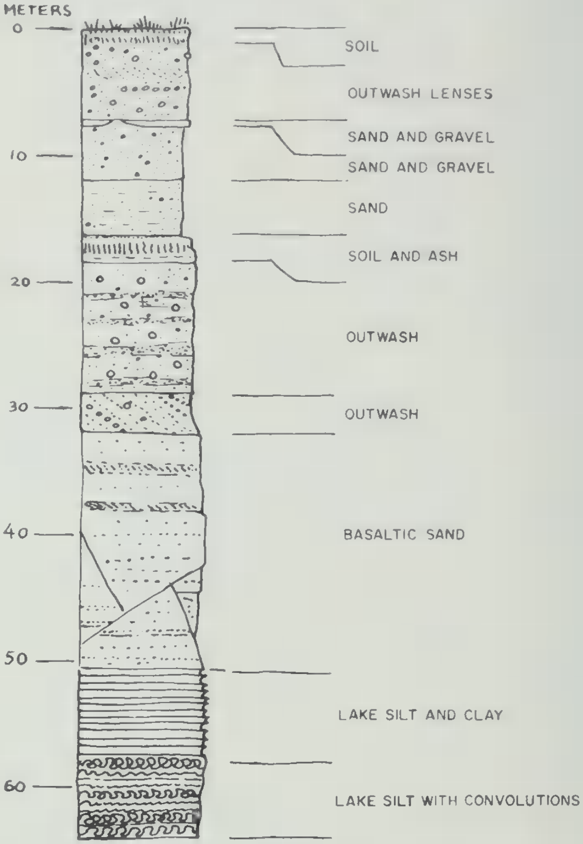


FIG. 3. Columnar Section of Sediments Exposed in the Eastern Part of the Main Scarp of the Largest Modern Landslide.

Abundant small folds within the lake sediments indicate slumping during deposition. Larger folds are associated with glacial or landslide activity after deposition but before the overlying stratigraphic unit was emplaced (Davis and Karzulovíc, 1961). Extensive folding of the lake sediments, however, was not caused by the 1960 landslides.

The surfaces of rupture of the two largest landslides were undoubtedly within the lake sediments. Beds which probably failed first were the well sorted, porous silts which crop out in 2- to 6-centimeter layers at river level. Some of these layers were so unstable that they were extruded like toothpaste when erosion of the new channel of Río San Pedro removed lateral support.

From 5 to 20 meters of stream-deposited pumice and basaltic sand rest unconformably on the lake sediments. The sand is overlain by 35 meters of coarse glacial outwash. The outwash has prominent crossbedding in the lower part and a continuous layer of weathered volcanic ash in the center. The layer is about 2 meters thick and contains several alternating bands of tan, grey, and brown ash. One of the darker bands, about 0.5 meter thick, is a buried soil. The ash layer served as a useful marker which helped to determine the original stratigraphic position of the landslide units.

A young till is exposed in the top of a cliff just east of the main scarp of the largest landslide. This till is intertongued with the upper few meters of the outwash.

The Pleistocene deposits lack evidence of extensive weathering and erosion. In addition, the A and B horizons of the modern soil on the outwash terrace are only 80 centimeters thick, with but a small amount of clay accumulated in the B horizon. These facts indicate that the deposits are young and were associated with the ultimate major glaciation of the region (Illies, 1960).

Landslide Structure

The largest landslide had an area of 1.26 square kilometers prior to the erosion of the new channel of Río San Pedro. The volume of material originally in the landslide is estimated to have been about 30 million cubic meters.

The largest landslide is divided into six structural units. These are, from north to south, (1) crown cracks, (2) main scarp, (3) debris apron, (4) tilted blocks, (5) large fractured block, and (6) rubble hills (figure 4). The area of crown cracks is confined to the eastern and western extremities of the crown. The largest crack is about 100 meters long and is parallel with the crown.

The main scarp has a gentle arcuate form with a few minor irregularities in plan view (figure 4). In vertical section, the scarp is truly impressive; it varies in height from 45 to 60 meters and extends in an east-west direction for slightly more than 1 kilometer. The face is inclined about 65 to 75 degrees from the horizontal.

The debris apron (fig. 5) extends for 100 to 200 meters outward from the base of the main scarp. The surface has a slope which varies between 10 and 12 degrees from the horizontal. From a distance, this surface has the appearance of a series of coalescing alluvial fans. A small part of the surface is made up of thin alluvial fans; however, most of the surface is made of debris which has cascaded from the scarp. All stratigraphic units exposed in the scarp have contributed material to the debris apron, but debris from units within the upper 20 meters is most abundant. Debris fragments vary in size from individual grains of fine silt to blocks of outwash gravel with estimated volumes as great as 6 cubic meters.

A series of tilted blocks borders the lower part of the debris apron (figure 6). Some of the large tilted blocks near the apron are partly surrounded by the debris;

other blocks are partly surrounded by small lakes. The largest block has a maximum length of 360 meters, a breadth of 50 meters, and a height of 28 meters. The larger blocks are composed of lake clays and silts. The smaller blocks measure only a few meters in each direction and are composed of outwash or a combination of lake sediments and outwash.

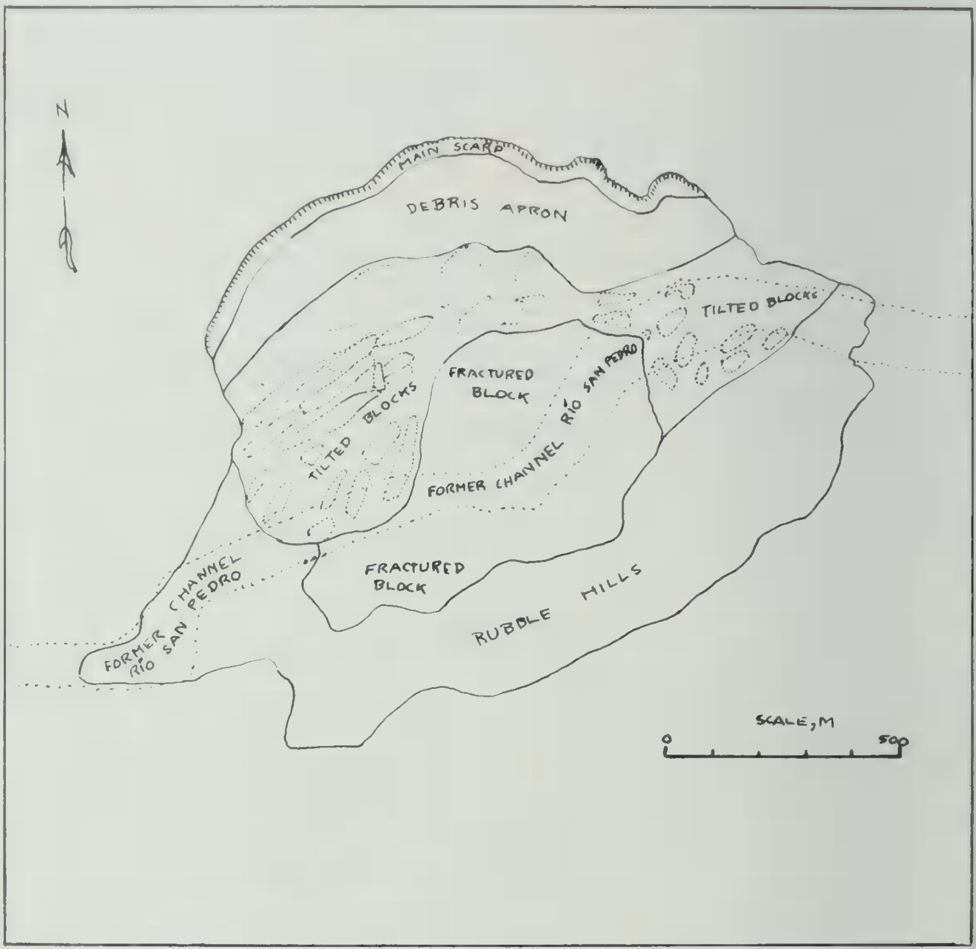
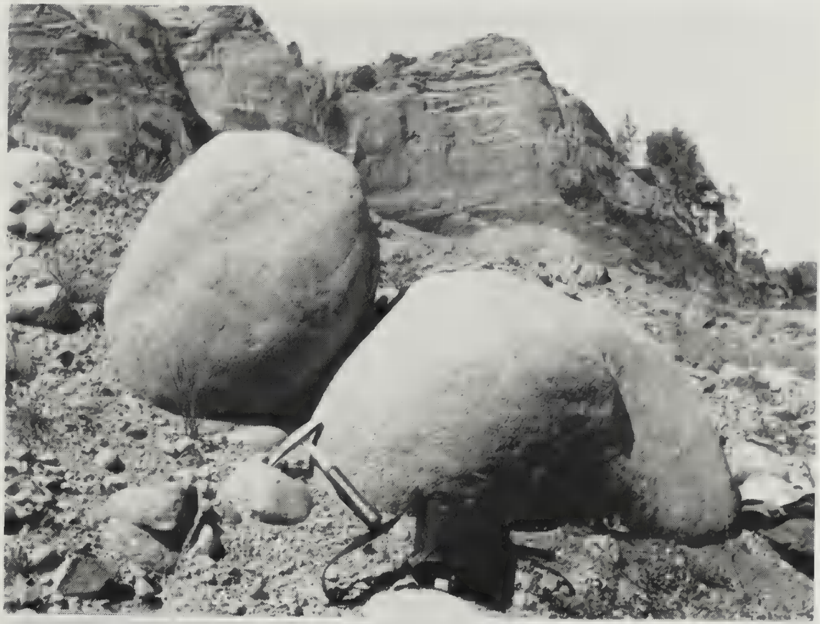


FIG. 4. Map of Structural Units in the Largest Modern Landslide. Largest rotational slump blocks are shown by dotted lines within the tilted block unit. Position of the former channel of Rio San Pedro and general margins of the landslide are from detailed maps prepared by ENDESA.

The blocks are elongated and mostly oriented northeast-southwest. This orientation is nearly perpendicular to the horizontal movement of the blocks. Strike and dip measurements were made of the strata within 31 blocks. The 3 largest blocks and 8 smaller blocks have dips of less than 15 degrees, except near fractures or in small zones affected by secondary slumping. The other blocks have dips ranging between 15 and 50 degrees, with the dips between 25 and 30 degrees being most common. The mean of 43 dip measurements made at various locations on all the blocks is 19 degrees.

Detailed topographic maps of ENDESA reveal several small valleys and offset ridges which are aligned for distances of as much as 300 meters. The fact that stratigraphic units are also offset along the alignments indicates that these linear



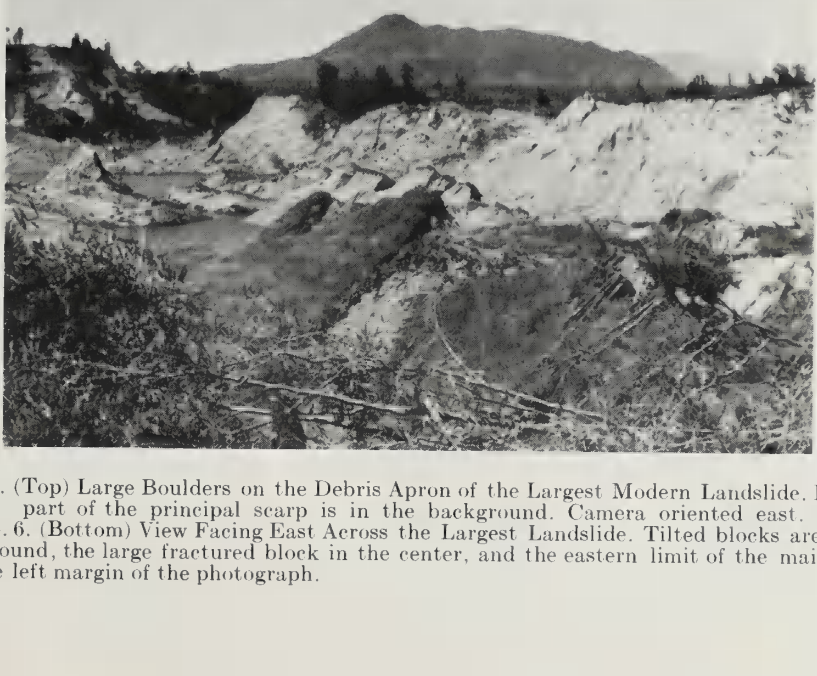


Fig. 5. (Top) Large Boulders on the Debris Apron of the Largest Modern Landslide. Eastern part of the principal scarp is in the background. Camera oriented east.

Fig. 6. (Bottom) View Facing East Across the Largest Landslide. Tilted blocks are in the foreground, the large fractured block in the center, and the eastern limit of the main scarp on the left margin of the photograph.

features are longitudinal "faults" within the landslide material. The horizontal displacement along the largest longitudinal "fault" is at least 20 meters, and possibly as much as 80 meters. Transverse "faults" are also present and are clearly defined by the boundaries of the tilted blocks.

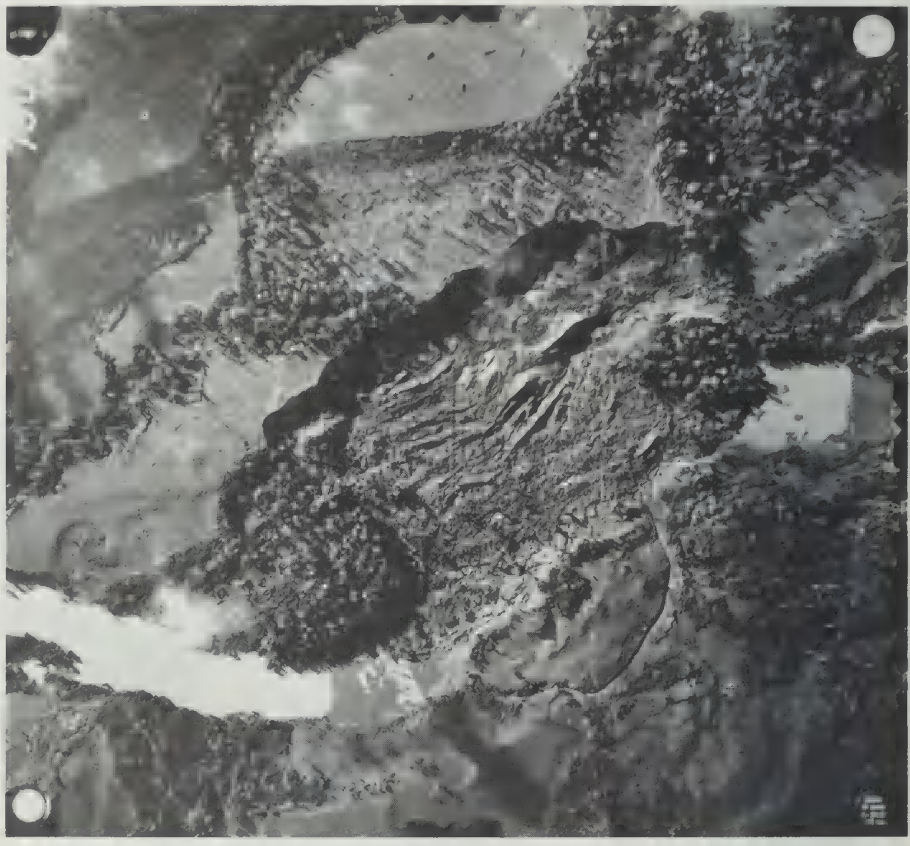


FIG. 7. Air Photograph of the Intermediate-size Landslide. Outwash terrace is at top (north margin) and hummocky surface of the ancient landslide is at the bottom of the photograph. Line southeast of the landslide is a diversion ditch under construction before the discharge of the lake. (Courtesy ENDESA.)

Folds having amplitudes of more than a few centimeters are generally absent from the slide deposits. Most changes of dip take place through successive displacements along cracks or by widening of cracks near the surface.

A large fractured block covers an area of 0.24 square kilometer, or roughly one-fifth of the original area of the landslide. The surface of this block is covered by the vegetation which existed prior to the movement of the landslide. Most of the trees are nearly upright, but there is some tendency for the trees along the north and south margins to be tilted inward toward the center. Locally near large cracks, trees are tumbled down or are tilted more than 30 degrees from the vertical.

Viewed from a distance, the surface of the large block has the appearance of a gently rolling grassy pasture with scattered trees. Actually, the surface is broken by hundreds of large cracks, and scarps of 1 to 5 meters are common near the margins of the block. The microtopography of the surface is so rough that walking is difficult over much of the block. The major features of the rolling topography were probably present prior to sliding; however, a large swale in the central part of the block reflects subsidence of the block over the former channel of Río San Pedro.

The rubble hills are a mass of highly fractured sediments mostly composed of lake clays and silts. This unit has a gradational contact with the tilted-block unit, particularly in the eastern part of the landslide. Individual fragments of material which make up the bulk of the rubble range in size from about 2 millimeters to 5 meters in diameter. Sizes between 0.4 and 2.0 centimeters appear to be most common. Outwash is rarely preserved in blocks, because it was crumbled by independent movement of individual clasts. Despite the chaotic appearance of the rubble, separate hills are underlain by material which is mostly homogeneous. That is, one hill is composed exclusively of volcanic sand, another of lake silts, another of outwash gravel, and so forth. In the western part of the unit, the material in the rubble hills is derived from the old landslide which borders the right flank.

The surfaces of the rubble hills are irregular and hummocky. They lack the elongated ridges which characterize the tilted-block unit. The outer zone of the hills is generally devoid of pre-landslide vegetation, but the inner part has much of the original vegetation on the surface. Slabs of sod are fractured and scattered on the surface, and the abundant trees and shrubs are tilted in random directions. Some of the trees are partly buried, but most of them appear to have remained on the surface during the violent movement of the landslide.

The intermediate-size landslide (figure 7) is 1.1 kilometers east of the largest landslide. It had an original surface area of 0.36 square kilometer and an original volume of about 6 million cubic meters. Material involved in this landslide was mostly lake sediment. The surface of the landslide is made up of a number of low ridges oriented more or less parallel with the main scarp.

The smallest of the three landslides is 200 meters east of the intermediate landslide. It had an original surface area of about 0.16 square kilometer and a volume of about 2 million cubic meters. Material in the landslide is probably a mixture of older landslide rubble, outwash gravel, and lake clays. The area was not traversed on foot. Air photographs, however, clearly show that material slid from both sides of the river and that most of the landslide is made of large rotated blocks.

Facts Related to Landslide Movement

The following list presents a number of important facts related to the movement of the largest landslide. Some of these facts have already been noted; others are taken from a previous publication (Davis and Karzulovíc, 1961).

1. The landslide movement was associated with a violent earthquake, which probably continued during the major period of sliding.

2. The lower 30 or 40 meters of lake clays were saturated with water prior to the landslide. This is evidenced by the abundance of springs which flow from the base of the main scarp.

3. The landslide antedated the onset of the winter rainy season.

4. The largest block moved about 300 meters horizontally and only 20 meters vertically.

5. Rotational movement was confined to blocks of a few thousand cubic meters or smaller.

6. Movement of the principal landslide mass was rapid and took place in less than 5 minutes. Local witnesses reported that a loud noise accompanied the movement. A large number of smaller landslides was produced within the larger landslide during a period of several months.

7. Highly porous layers of silt, sand, and volcanic ash from one to two centimeters thick are present in the central and lower part of the lake sediments.

8. No large volume of a liquid-like suspension of clay, silt, and water was extruded from beneath the landslide debris. Material extruded was mostly composed of small angular fragments of lake clay and may have been semiplastic.

9. A well developed joint system exists in the lower lake silts, which have not been affected by the landslide.

10. Early photographs indicate an ancient landslide occupied part of the recent landslide area.

INTERPRETATION OF MOVEMENT

The movement which produced the largest landslide is thought to have been mostly block gliding and lateral spreading. Secondary movements within the landslide were rotational slumping and debris falls. Following erosion of the new channel of Río San Pedro, numerous small mudflows developed. Small debris falls and sand runs have continued up to the time of writing of this report.

The sequence of events that is postulated to have taken place during the movement of the largest landslide is shown in figure 8. The first strong seismic activity produced a collapse of the structure of various thin beds of highly porous silt and fine sand. This left the overlying mass of material supported entirely by a mixture of water, sand, and silt, which had no strength. Continued seismic activity started a large block of sediments moving toward the river. This motion produced extensive fracturing in adjacent silt and clay beds. The fractured material became semifluid when mixed with water from the river as well as water from the collapsed beds of silk and sand. As the block moved out across the river bed, smaller blocks broke off behind and, in turn, produced rotational slumping. Meanwhile, the main scarp produced a large number of debris falls, which began to fill the void left by the movement of the blocks. After movement of the large block had started to diminish, the weight of the block upon the underlying fractured sediments produced a rapid extrusion of this semifluid material. The fluidity of this material was undoubtedly increased by the continued strong seismic activity, which aided fracturing, released more water by producing compaction, and kept thixotropic material in motion.

Dominant movement within the intermediate-size landslide was probably lateral spreading; that of the smallest landslide, rotational slumping. Not enough data were collected to reconstruct details of these landslide movements.

ANCIENT LANDSLIDES

Many deposits of ancient landslides flank Río San Pedro near Lago Riñihue. Three are shown in figure 2. The largest of these is on the south side of Río San

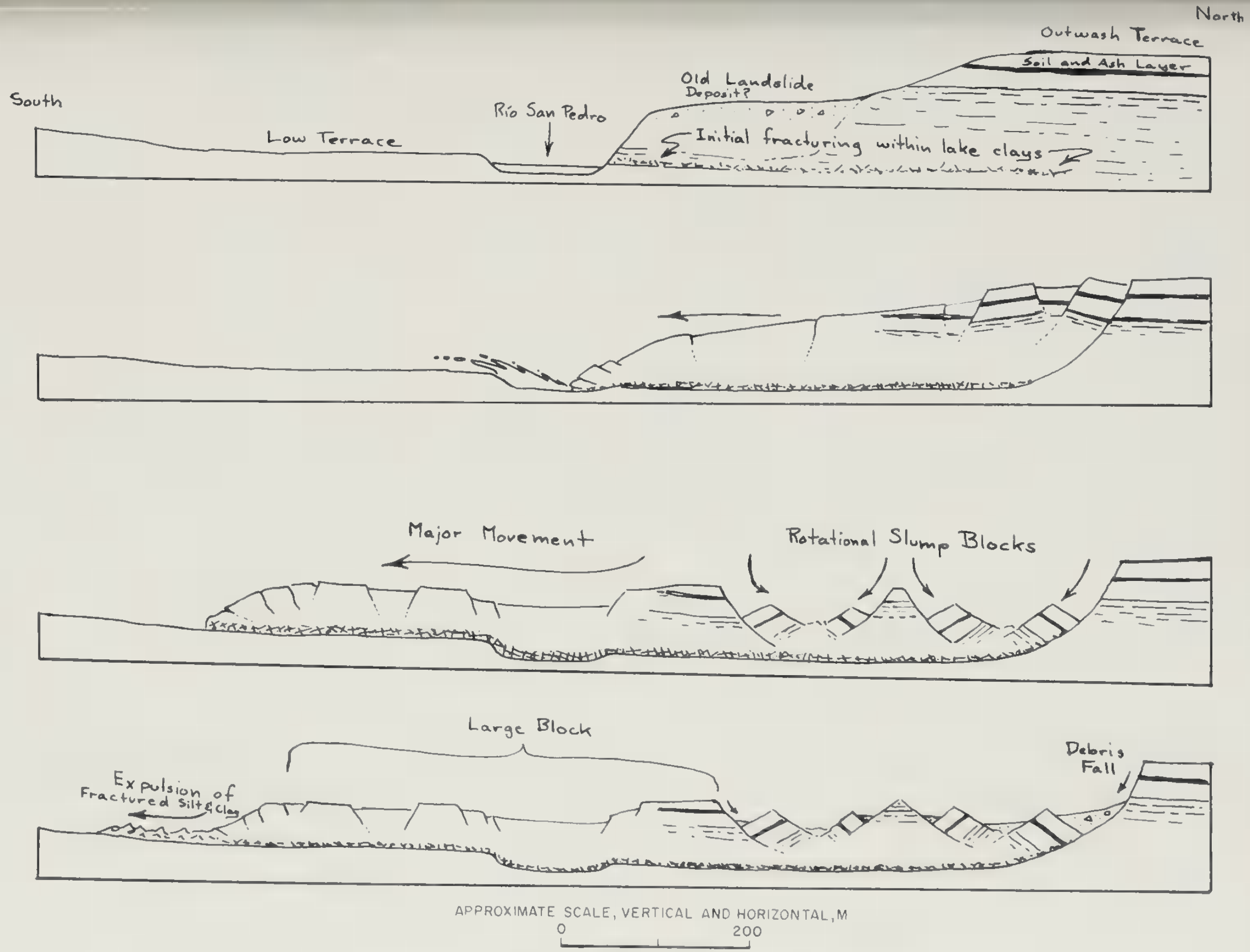


FIG. 8. Cross Sections Showing an Interpretation of Movement Within the Largest Modern Landslide. Scale and surface profile are only approximate.

Pedro, opposite the smaller landslides of 1960. The principal scarp, linear ridges, and hummocky topography of the large ancient landslide can be seen clearly on air photographs. The continuity of ridges suggests that the landslide was formed as a single unit and that it was not formed by the coalescence of several landslides. Its surface is partly covered by a mature hardwood forest which must be at least 100 years old. The total area of the landslide is 2.8 square kilometers. If an average thickness of the landslide deposit is assumed to be 40 meters, then a volume of 112 million cubic meters is indicated.

Weischet (1960) suggested that this ancient landslide originated in 1575, the date of the large earthquake that was followed by the devastating flood. Some of the smaller landslide remnants may also date from this earthquake. Thus, from events during the past 400 years, it is evident that much of the widening of the valley of the upper Río San Pedro has been caused by earthquake-triggered landslides.

ACKNOWLEDGMENT

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GENERAL CHARACTERISTICS OF ACTIVE ANDEAN VOLCANOES AND A SUMMARY OF THEIR ACTIVITIES DURING RECENT CENTURIES

By Lorenzo Casertano

(Translated by Oreste W. Lombardi)

ABSTRACT

An oceanic deep lies off the Chilean coast, bordered on the east by a coastal mountain range, a discontinuous central valley, and the high cordillera of the Andes.

The Chilean volcanoes are found on lineaments that in general coincide with, or are sub parallel to, axis of the Andes. In north Chile they lie along *en echelon* fractures and, in some cases, along transverse fractures. In the south, the alignment of the volcanoes lies west of the axis of the Andes. Where the Central Valley is not well developed, active volcanoes are scarce.

Recent lavas range from basalt in the south to rhyolite in the north. Volcanic activity appears to be decreasing.

Details are given of individual volcanoes, and a list of active Andean volcanoes south of Volcan Misti is presented with a historical account of their activity.

Introduction

The volcanism of Chile is an integral part of the general picture of geologic phenomena not only of Chile and the South American continent but of the whole circumpacific "circle of fire." *Watanabe* (oral communication, 1960) has observed that in Southern Chile, as in Japan, starting from the Pacific Ocean one finds a coastal cordillera followed by a longitudinal valley, an alignment of active volcanoes, and finally a second cordillera (in Chile, the "Cordillera de los Andes"). To complete the similarity of the Chilean and Japanese zones relative to the ocean, it is only necessary to add their respective oceanic deeps that lie offshore. Hence an explanation of the origin and general development of the Chilean volcanoes must be related to that of the whole circle of fire.

These volcanoes have, without doubt, been affected by particular and local elements but only in a secondary sense. In Chile, for example, in those latitudes where the longitudinal valley is not well developed there are no modern volcanoes, *Pissis* (1875, p. 118) and *Brüggen* (1950). A secondary cause, such as continental drift or the rotation of the Pacific Ocean basin, could have intervened, as shown by *St.-Amand* (1957) and by *Benioff* (1957).

The primary and general cause of the volcanism of the whole circle of fire is probably explainable by the hypothesis that relates the birth of the volcanoes, together with the orogenesis of subcrustal magma, to horizontal temperature gradients in the limited zones between the continents and the oceans, *Rittmann* (1947–1948).

The Chilean volcanoes lie along lines that in general are parallel to the axis of the Andean Cordillera. *En echelon* alignments are found, with some transverse lineaments in northern Chile, where major groupings of volcanoes are present. This is in all probability caused by a series of secondary fractures, perhaps dependent upon the north-south fracturing. In the south, the main alignment of the volcanoes lies west of the main axis of the mountains.

HISTORICAL DEVELOPMENT AND PETROLOGY

Chilean volcanoes apparently violate the general rule that magmas become more acidic as they cool. *Munoz Cristi* (1956) stated that the first cycle of Chilean volcanism developed at the end of the Permian and continued to the early Triassic, with the emission of potassium rich (keratophyric) and felsitic quartz porphyry. The second cycle began in mid-Tertiary with the emission of rhyolitic lava followed later by trachytic lava. Andesites with augite and hypersthene, followed by basalts, were first emitted in the Puna de Atacama during the Pliocene. The same sequence, on the whole, holds for southern Chile; however, in later epochs (including the Quaternary) some trachytes and liparites, as well as basalts, were emitted, *Klohn* (1946), *Kittl* (1933), and *Brüggen* (1950).

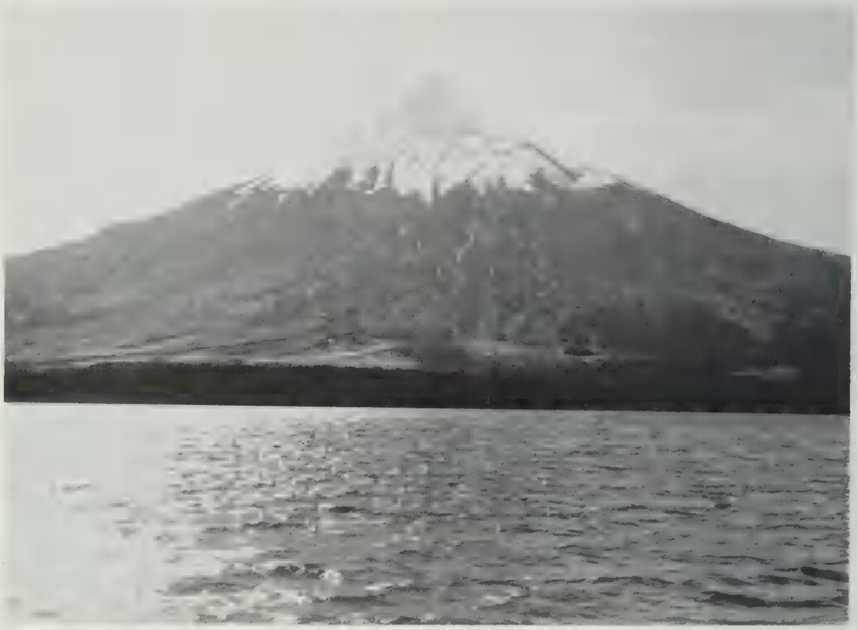

FIG. 1. East Side of Osorno (No. 32), El. 2,660 m. Looking west from Lago Todos Los Santos.

The recent lavas vary from basalt in the south to rhyolite in the north. According to *von Wolff* (1929) the recent lavas from Patagonia to Quizapu, in the Descabezado group, appear to grade from basalt to andesite. *Stone* and *Ingerson* (1934), however, report that all of the recent lavas between Nevadas de Chillan and Calbuco are olivine basalts, except for Calbuco itself where hypersthene basalt without olivine is the norm.

The contrary behavior of Chilean volcanoes may be explained by assuming that the material that emerged from the first eruptions absorbed acidic material from the upper strata of the magmatic pocket, thus acquiring a composition differing from that of the main body of magma. With successive eruptions, the rising magma absorbed material from previous eruptions; thus the difference between the erupted material and the main body of the magma became less each time.

PRESENT STATE OF ACTIVITY

The frequency and potency of Chilean volcanic activity has decreased, and this is most evident in northern Chile, where only 13 out of more than 1,000 recent volcanoes remain active. In southern Chile the percentage of active recent volcanoes is much greater, and the eruptions are more frequent and potent than in the north.

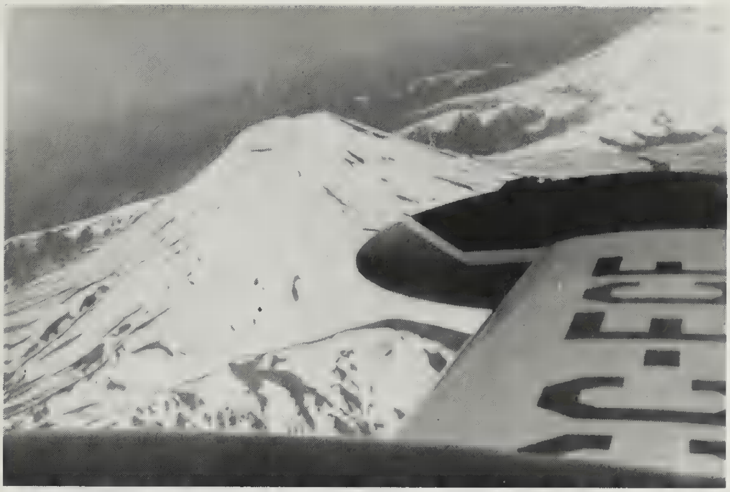

FIG. 2. East Side of Lonquimay (No. 26), El. 2,822 m. At the far right is the extinct volcano Tolguaca.

Casertano (1959) has concluded that Chilean volcanoes are becoming extinct, beginning in the north and progressing southward. *Cecioni* and *Garcia* (1960) observed that the Andean diorite (the Andean batholith) appears to get younger going from north to south. The previous observation suggests that Chilean volcanism began in the north and developed southward, and, likewise, volcanic extinction, beginning in the north, will progress southward. Finally, the complex variation of activity through the course of time appears to have been normal. The first eruptions appear to have come out of fissures several kilometers in length. The first eruptions were probably strongly effusive; however, explosive eruptions have been predominant.

MORPHOLOGY

The morphology of active Chilean volcanoes is diverse. The volcanoes, however, are all stratified and rise on the order of 1,500 to 2,000 meters above base elevation (base elevation declines from 4,000 meters in the north to near sea level in the south). The elegant cones such as Osorno, Villarrica, and Lonquimay are found in sharp contrast to the inelegant masses of Descabezado, the complex of Nevadas de Chillan, and the complex mass of Calbuco (figures 1 to 5). The craters of active Chilean volcanoes range in diameter from a few hundred meters at Osorno and Villarrica to several kilometers at Puyehue.

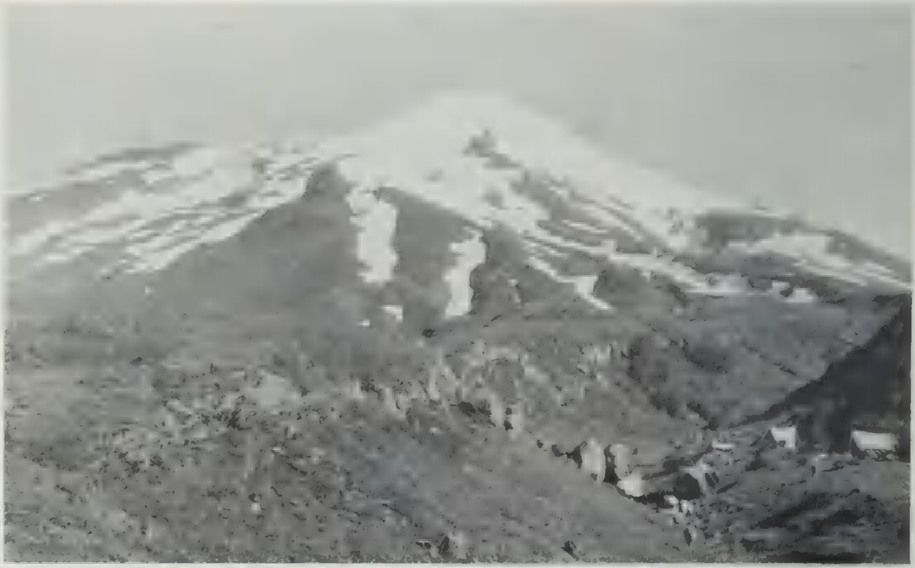

FIG. 3. North Side of Villarrica (No. 28), El. 2,840 m.

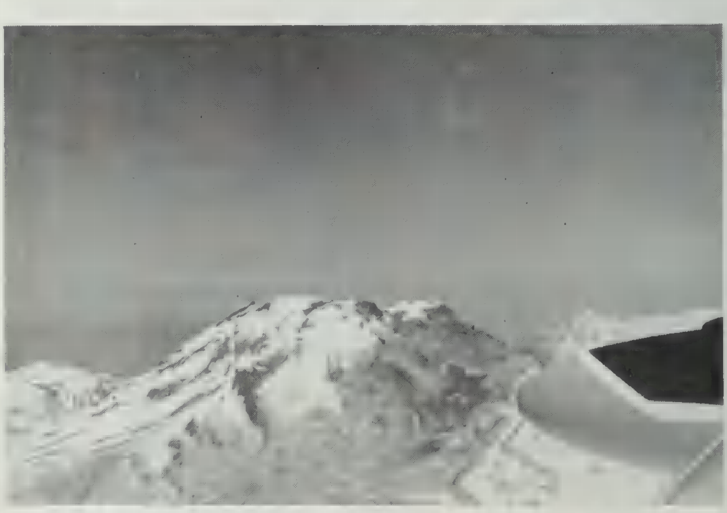

FIG. 4. West Side of Descabezado Grande (No. 22), El. 3,830 m. Note the ash on the snow.

Active Chilean volcanoes have diverse systems of enclosure as shown by the following examples: (1) The two active volcanoes of the Riñihue group, Shoshuenco and El Mocho, correspond to the classic example of Somma and Vesuvius, respectively. (2) Antuco appears to be two volcanoes, with one almost perfectly super-

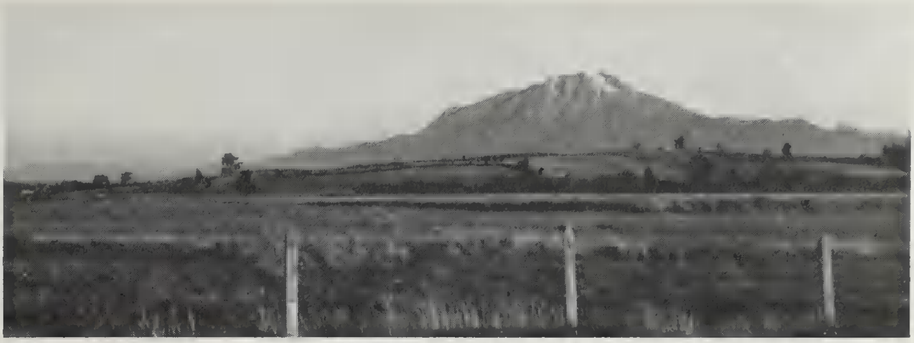

FIG. 5. North Side of Calbuco (No. 33), El. 2,015 m. There is a small glacier on the south side of Calbuco.

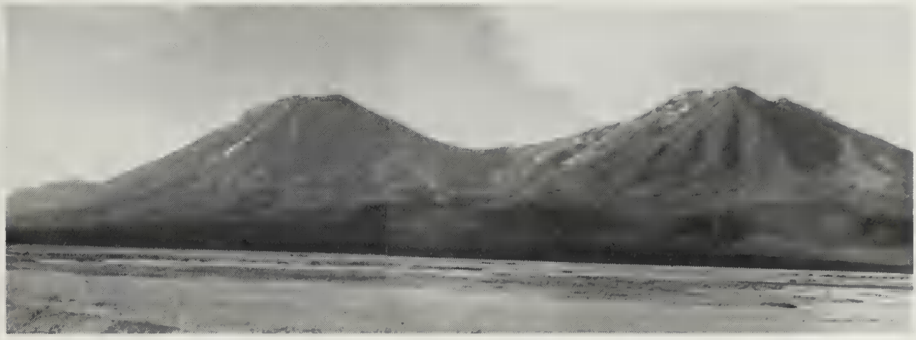

FIG. 6. Twin System; San Pedro (No. 11), El. 6,159 m, Left, and San Pablo, Right. The perennial river San Pedro is in the foreground.

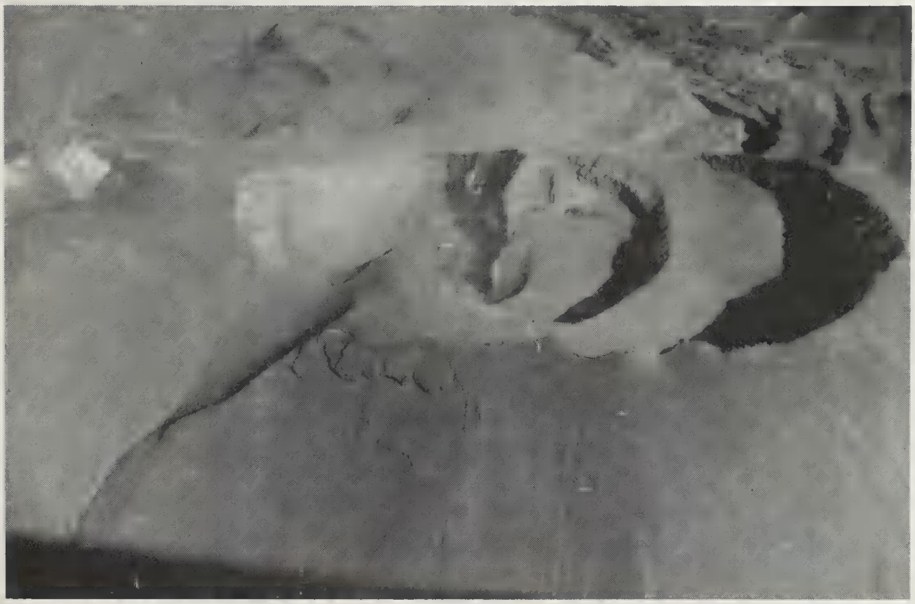

FIG. 7. The Twin Craters of Láscar (No. 14), El. 5,641 m.

imposed on the other. (3) The large enclosure of Osorno is almost completely destroyed. (4) Peteroa consists of an active crater inside a very large ancient inactive crater. Continued activity could cause the inner crater of Peteroa to grow into a cone; thus the author called it a "system of enclosure in formation."

An excellent example of a twin system in which the two eruptive foci are sufficiently distinct to be separately named is the San Pedro-San Pablo system (figure 6). Two other twin systems are those of Volcano Láscar and of Volcano San José. In both systems, the eruptive foci are so close that they are not separately named. In the Láscar system, an elongate mass oriented east-west, the two foci have been converging one upon the other with the passage of time (figure 7). The eastern focus is active at present, but the western focus seems to be extinct. Volcano Láscar has been described in detail by *Casertano* and *Barozzi* (1961).

There is no example of a true maar among Andean volcanoes; however, there are some crateric lakes. One of the best examples of a crateric lake in the Andes is the one in the crater of Los Copahues, in which the water is acidic and warm. The 1955 eruption of Carrán, in the Nilahue group, formed the crater lake of Carrán in the same zone that had contained a previous crateric lake, Laguna Negra. Laguna Negra dried up in 1907 following the eruption of Riñinahue one kilometer from Carrán. *Brüggen* (1950) indicates several other maars.

Active Andean Volcanoes

Reports of volcanic activity in Chile have come largely from travelers. First-hand authoritative reports are infrequent. For these reasons, it is difficult to characterize individual volcanoes.

Appendix A is a map showing the location of the active Andean volcanoes. (It appears separately as an insert at the back of this number.)

Appendix B lists the exact locations, elevations, and eruptions of active volcanoes for which, in the author's opinion, reliable reports are available. The authors cited are listed in the Bibliography.

APPENDIX A

An insert at the back

APPENDIX B

ERUPTIONS OF ANDEAN VOLCANOES

1. *Misti.* 16°15′S 71°25′W, 5,842 meters. Activity 1784, 1826, Aug. 1830, Aug. 1831, 1868, and Sept. 1869, *Sapper* (1917, p. 284). Only fumarolic activity at end 19th century.
2. *Ubinas.* 16°20′S 70°53′W, 5,300 meters. Explosive eruption May 28, 1867, Fuchs (1868); *Gutenberg and Richter* (1949). Ash and explosive eruption 1865. Press reports lava eruption 1937.
3. *Omate.* 16°37′S 70°54′W, 4,000 meters. Explosive eruption Feb. 1660, *Meyendorff* (1894, p. 265). Eruption 1667, *von Humboldt* (1868, P. 549).
4. *Tutupaca.* 16°55′S 70°25′W, 5,000 meters. Explosive eruption 1802, *Paz Soldan* (1862, p. 15).
5. *Tacora.* 17°43′S 69°47′W, 5,980 meters. Solfataric and fumarolic manifesta-

tions only, *Brüggen* (1950). Sulphur deposits associated with Tacora are being exploited.

6. *Guallatiri*. 18°25′S 69°06′W, 6,060 meters. Ash and steam emission in previous centuries, *Gutenberg and Richter* (1949). Vapor and ash early 19th century, *Pentland* (1835). Strongly active, emitting incandescent material at night, 1913, *Buchtien* (1914). Similar activity mid-July 1959. Minor activity Dec. 2, 1960, noted by author. Sulphur deposits are associated with Guallatiri.
7. *Isluga*. 19°09′S 68°50′W, 5,530 meters. Erupted Aug. 1863, *Mercalli* (1907, p. 361). Erupted Aug. 1869, reported independently by *Perrey* (1871) and *Fuchs* (1870). *Sapper* (1917, p. 286) accepts only the second eruption. *Fuchs*, cited by *Sapper* (1917) reports eruption 1878. *Brüggen* (1950a) lists major eruptions 1868, 1869, 1877, and 1878, and minor eruptions 1863 and 1885. Some activity 1913, *Buchtien* (1914). The author observed no activity Dec. 2, 1960. Sulphur deposits at base.

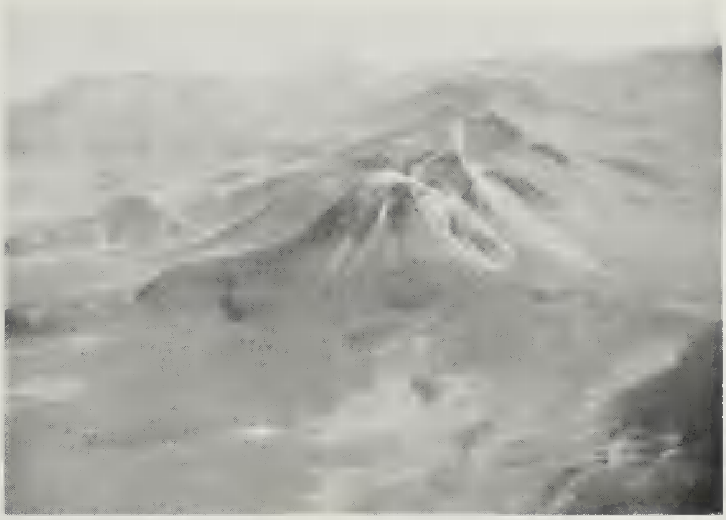

FIG. 8. Irruputuncu (No. 8), El. 5,165 m. Irruputuncu is in the center, and behind it is a broken ridge extending to C. Copa, looking northeast. Note the north-south fault cutting the southwest foot of Irruputuncu. Other faults may be seen.

8. *Irruputuncu*. 20°44′S 68°34′W, 5,165 meters (figure 8). Scant reports of activity. Solfataric activity Dec. 2, 1960, noted by author. Sulphur deposits associated with this volcano.
9. *Olca*. 20°56′S 68°31′W, 5,310 meters. In solfataric state. Solfataric activity 1865 to 1867, *Brüggen* (1950a). Dec. 2, 1960, noted by author. Sulphur deposits being mined.
10. Ollagüe or Oyahue. 21°18′S 68°12′W, 5,869 meters (figure 9). Solfataric manifestations 1854, *Philippi* (1860); 1884, *Bertrand* (1885); 1888, *Meyendorff* (1909); 1927, *Brüggen* (1950a); and 1960, by author. Sulphur deposits being mined.
11. *San Pedro*. 21°53′S 68°24′W, 6,159 meters (figure 6). Eruption May–Aug.

1910, *Martin* (1901 and 1923). A preceding eruption, assigned to 1877, was reported by *Martin* (1923) and, assigned to 1891, was reported by *Martin* (1901). It is not possible to tell on which of the two dates eruption occurred or whether there were two eruptions. Explosive activity 1911, *Bergeat* (1914). Minor activity Dec. 2, 1960, noted by author.

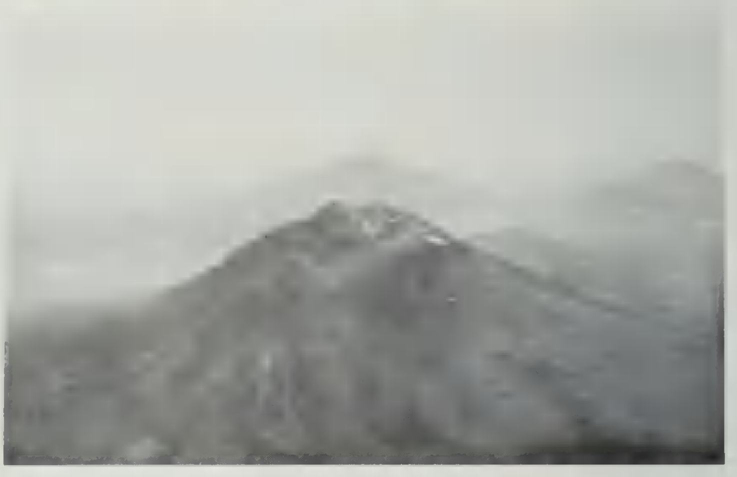

FIG. 9. Ollagüe or Oyahue (No. 10), El. 5,869 m. Note the fumarole to the right of the crater. Looking east behind Ollagüe is C. Coyumiche.

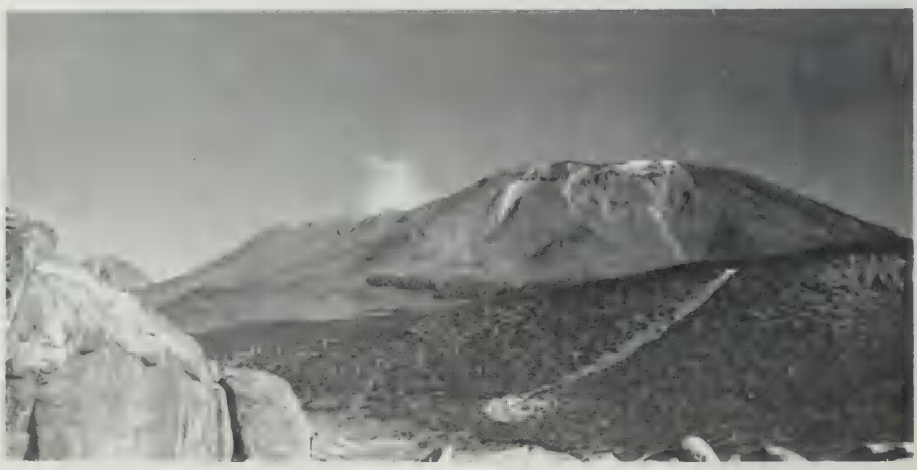

FIG. 10. The System of Láscar (No. 14), El. 5,641 m. Looking east.

12. *Tatio.* 22°24′S 68°01′W, 5,314 meters. Geyser field at foot, *Brüggen* (1943). Volcano appears inactive.
13. *Putana.* 22°34′S 67°52′W, 5,890 meters. Continuous fumarole activity, *Brüggen* (1950). Fumarolic activity 1886 to 1888, *San Roman* (1896, p. 238); about 1900, *Risopatron* (1911); 1960, noted by author. Sulphur mined.
14. *Láscar.* 23°22′S 67°44′W, 5,641 meters (figures 7 and 10). Erupted 1848,

Philippi (1860); 1853–1854, *Brüggen* (1950); around 1875, *San Roman* (1911); 1933, *Brüggen* (1950); March 1960. A low level of activity from 19th century to present, *Casertano and Barozzi* (1961).

15. *Llullaillaco.* 24°43′S 68°33′W, 6,723 meters. Minor activity 1854, *Philippi* (1860). Eruption (possible lateral) 1868, *Astaburuaga* (1899). Activity 1877 that *Geinitz* (1878) associates with earthquake of Iquique. Author observed no activity Dec. 1, 1960.
16. *Lastarria.* 25°10′S 68°31′W, 5,700 meters. In solfataric state. Fumarolic activity end 19th century, *Darapsky* (1900); beginning 20th century, *Risopatron* (1924 and 1906); Dec. 1960, noted by author. Sulphur deposits associated with volcano.
17. *Nevado Ojos del Salado.* 27°07′S 68°32′W, 6,885 meters. No information until Feb. 1937, when Polish expedition climbed the volcano and observed fumarolic activity. Similar activity 1956, *Lliboutry* et al. (1958).
18. *Tupungatito.* 33°24′S 69°48′W, 5,640 meters. Guide who accompanied *Darwin* (1840) reported smoke. Similar behavior reported during earthquake of Mendoza 1861, *Monteessus de Ballore* (1912, p. 35). Eruption 1829, *Meyen* (1834). Questionable eruption 1881, *Brüggen* (1950). Activity 1889–1890, *Moericke* (1894). *Risopatron* (1903) compares the glows from Tupungatito seen at night Jan. 1897 and April 1901 with the "summer lightning" that *Gillis* (1855) and *Domeyko* (1859) refer to as "relampagos de calor." Activity April 12, 1897, *Vines* (1899). Activity Feb. 15, 1907 seen by excursionists *Abascal Brunet* (1940). The crater of Tupungatito was first reached in 1925 by excursionists who reported some activity, *Abascal Brunet* (1940). Eruption Jan. 1958. *Stohr* (1958). Some activity Oct. 1959, noted by author. Press reports ash fall in Argentina March 1959. Columns of volcanic ash observed at a distance, rising from the zone of the volcano, in May and August 1961, *Casertano* (1962).
19. *San José.* 33°48′S 69°55′W, 5,830 meters. Erupted explosively Nov. 19, 1822, in connection with earthquake in Santiago and Valparaiso; was continuously active until 1838, *Pissis* (1850). Activity Feb. 1831, *Meyen* (1834). Eruption 1881, *Ochsenius* (1884.) Emission of smoke from crater in April 1896 and March 1897, *Risopatron*, (1903). *Risopatron* (1903) attributes smoke seen by *Caro* in April 1895 to San José, which *Caro* himself attributed to Maipo, now considered extinct. Eruptions 1931 and 1941, *Brüggen* (1950). No activity in crater 1875, *Zegers* (1875); in 1920, *Gewinner* (1920); nor noted by author, Oct. 1959 and July 1960. Eruption reported in connection with 1843 earthquake in Valley of Piuquenes, *Pissis* (1850) reports small cinder cones formed in various places in the area. Author considers this eruption questionable.
20. *Tinguiririca.* 34°49′S 70°21′W, 4,300 meters. Only solfataric and fumarolic activity throughout its known history.
21. *Peteroa.* 35°15′S 70°34′W, 4,090 meters. Eruption 1600, *Daubeny* (1848, p. 495). Large eruption beginning Dec. 3, 1762, *Molina* (1782, p. 42). Eruptions 1835, 1878, Sept. 1889, and Jan. 1890, *Fonck*, according to *Martin* (1901). Minor activity in or before 1860, *Pissis* (1860). Minor activity 1890–1895, *Stange* (1898). The Boletin del Servicio Sismologico (1937) reports that after a relatively long period of rest, Peteroa became active again in 1937. *Gerth*

(no date) mentions that he observed this same activity when he visited the Peteroa area during the same period. Excursionists visiting the crater in 1955 saw no activity. Strong activity in crater, Nov. 1959, July 1960, and Jan. 1962, noted by author.

22. *Descabezado Group* consists of *Descabezado Grande* 35°35′S 70°45′W, 3,830 meters, and *Cerro Azul* 35°39′S 70°46′W, 3,810 meters. *Quizapu*, a new volcano, is a lateral crater of Cerro Azul (fig. 11; see also fig. 4). These volcanoes were considered inactive until Nov. 26, 1846, when a lateral crater opened between Descabezado Grande and Cerro Azul and extruded a great current of lava, *Domeyko* (1850). It is not certain whether this lateral crater or some other new crater was given the name Quizapu. Quizapu was continuously active through the 20th century until April 10, 1932, when it erupted with extreme violence, perhaps the most violent volcanic explosion known in Chile. This eruption lasted only 2 days, *Fuenzalida* (1943). Another lateral crater that opened in June 1932, *Fuenzalida* (1941 and 1942) northeast of Descabezado Grande, and erupted through most of 1932, should be considered as a continuation of Quizapu. A fumarole was seen in the crater of Quizapu in 1959.

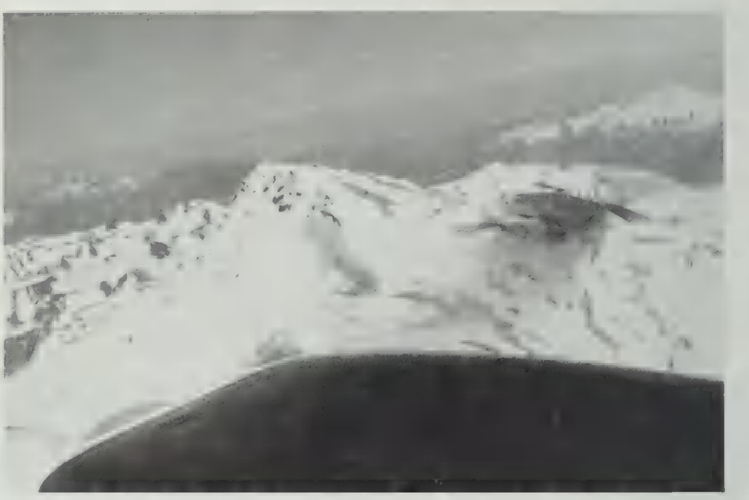

FIG. 11. Cerro Azul of the Descabezado Group (No. 22), El. 3,810 m. The lateral crater on the right is Quizapu.

23. *Nevados de Chillan.* 36°49′S 71°26′W, 3,170 meters. An alignment of several volcanic cones going from northwest to southeast as follows: *Cerro Blanco* or *Nevado*, *Volcan Nuevo* or *Chillan Nuevo*, and the older *Volcan Viejo* or *Chillan Viejo*. *Cordora y Figueroa* (1862, p. 17), *Havestadt* (1777), and *Gomez de Vifaurre* (1886, p. 62) report smoke in 1750 et seq., probably from Chillan Viejo. A new crater on west slope of Cerro Blanco erupted from June 1861 to Dec. 1862, *Pissis* (1875, p. 120); *Philippi*, (1862); 1864, *Pissis* (1875).

Intensified fumarolic activity northwest of Chillan Viejo Aug. and Sept. 1906 was said to be connected with the earthquake of August 1906 that destroyed Valparaiso. It has been said that on this occasion a new cone formed, *Steffen* (1907); *Stone and Ingerson* (1934); *Stone* (1935); *Brüggen* (1950). The author is of the opinion that there was no direct connection between the earthquake of August 1906 and the intensified fumarolic activity. Also discounted are reports of the formation of a new cone. The engineer, Lira, visited this area and ruled out such relationships (*Lira*, 1906, published only in newspapers).

Chillan Nuevo is a new crater (questionable) that opened in 1906, *Steffen* (9907). *Sapper* (1927, p. 354) reports an eruption of Nevados de Chillan in 1927, which is questioned because if was not cited by *Stone* (1935), *Stone and Ingerson* (1934) who visited the area in 1929. *Stone* (1935), *Stone and Ingerson* (1934) observed plumes of smoke erupting from Chillan Nuevo. *Brüggen* (1950) reports that Chillan Nuevo was in "stromboli-like" activity until 1940, while in 1950 it emitted only a small white cloud. In Nov. 1959, no activity could be seen at Chillan Nuevo from an airplane.

24. *Antuco.* 37°24′S 71°22′W, 2,985 meters. Erupted about end Jan. 1752, *Havenstadt* (1777, p. 905); 1820, 1839, *Fonck*, unpublished, cited by *Martin* (1901); 1852 to 1853, *Smith* (1855, p. 86); *Gillis* (1855, p. 4); 1861, *Pissis* (1875, p. 123). Minor activity 1806, *de la Cruz* (1910a, p. 131; 1910b, p. 273); 1828, *Poeppig* (1835, p. 365); 1845, *Domeyko* (1848); 1863, *Thompson* (1863); and 1869 (which continued to 1884), *Pissis* (1875b, p. 17); *Brüggen* (1950). Some activity 1929, probably fumarolic, *Stone* (1935), *Stone and Ingerson* (1934). No sign of activity Nov. 1959.
25. *Los Copahues.* 37°51′S 71°10′W, 3,010 meters, *de Ovalle* (1646, p. 15), *Rosales* (1877, p. 202), and *Molina* (1782, p. 42) referred to Los Copahues as Notuco. The younger crater of Los Copahues contains a small lake warmed by fumarolic activity. Los Copahues probably erupted between the 17th and 19th centuries. Fumarolic activity in the crater probably began early in the 20th century.
26. *Lonquimay.* 38°22′S 71°35′W, 2,822 meters (see figure 2). Eruption 1853. Minor activity June 1887 and Dec. 1889, *Fonck* according to *Martin* (1901).
27. *Llaima.* 38°42′S 71°42′W, 3,124 meters (fig. 12). Erupted 1640, *de Ovalle* (1646, p. 15 and 246), *Rosales* (1877, p. 203); Dec. 1751, *Havestadt* (1777, p. 901); 1852, *Anrique and Silva* (1902, p. 266); 1876, *Subercaseaux* (1883, p. 122); Jan. 0887, *Fonck* according to *Martin* (1901); 1889, *Brüggen* (1950); 1895, *Guevara* (1898, p. 17); 1896, *Hauthal* (1903); May 12 to 14, 1903, *Martin* (1923, p. 84), *Stone and Ingerson* (1934), *Stone* (1935); Oct. to Dec. 1927, *Stone* (1935), *Stone and Ingerson* (1934); 1941, *Brüggen* (1950); and 1955 and 1957. Many reports of minor activity between the foregoing eruptions: 1862–64, *Pissis* (1875, p. 124); 1883, *Subercaseaux* (1883, p. 64); 1893, *Knuttel* (1894); 1907–08 (press). Perhaps eruption 1912, *Martin* (1923); 1914, *Vogel*, cited by *Sapper* (1917, p. 292); 1917, *Martin* (1923); 1929, *Stone and Ingerson* (1934), *Stone* (1935).

Fumarolic activity in the principal crater and in the area between it and an adventitious crater situated to the southeast at end 1959, 1960, and 1961, noted by author.

28. *Villarrica.* 39°25′S 71°57′W, 2,840 meters (see figure 3). Erupted 1822, *Darwin* (1838); Feb. 1869, *Vidal Gormaz* (1869), *Philippi* (1869); April 1874, *Anrique and Silva* (1902, p. 166); 1883, *Martin* (1901); Oct. to Dec. 1908, *Liutgens* (1909); Dec. 1920, *Stone* (1935), *Stone and Ingerson* (1934); Dec. 1958 to Feb. 1959, noted by author. Minor activity 1558, *Ercilla y Zunica* (canto 34); 1640,

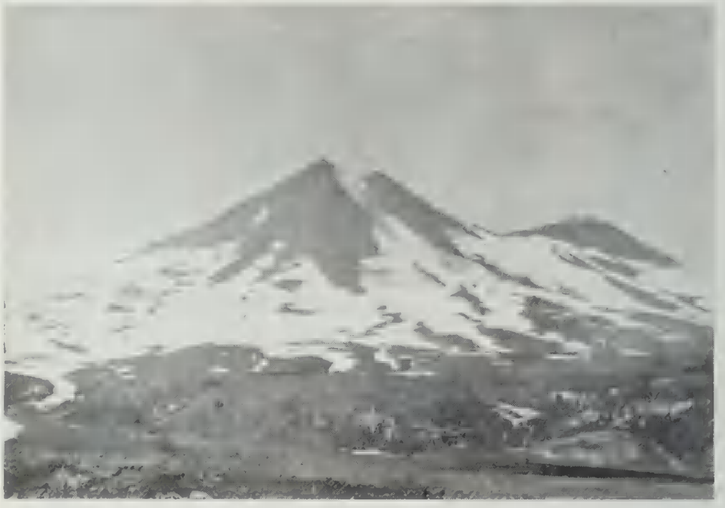

FIG. 12. West Side of Llaima (No. 27), El. 3,124 m. Note the glacier in the foreground covered by pyroclastics.

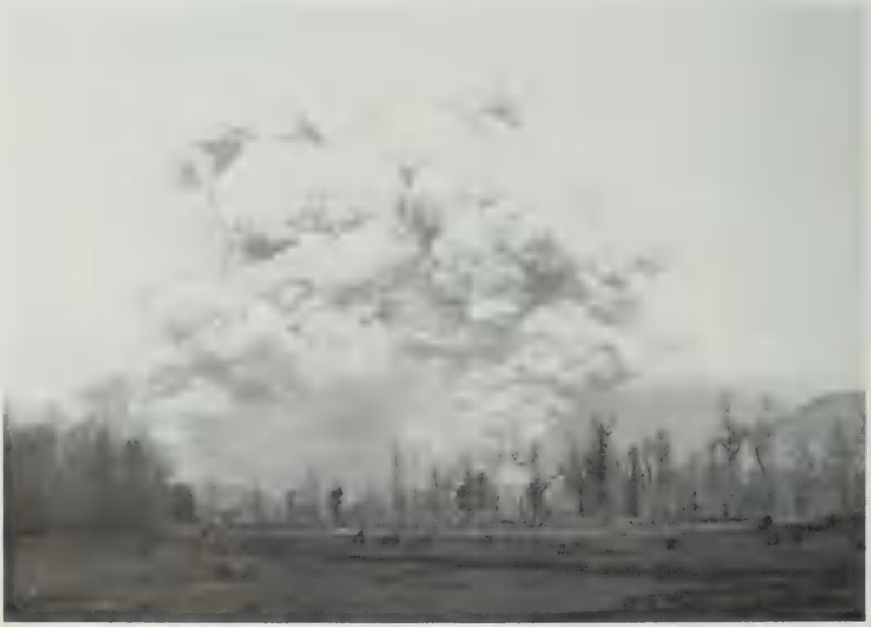

FIG. 13. Carrán, of the Nilahue Group (No. 30), El. 300 m. The 1955 eruption of Carrán.

de Ovalle (1646, p. 15), *Rosales* (1877, p. 202); late 18th century, *Molina* (1872, p. 42); 1806 and early 19th century, *De La Cruz* (1910b, pp. 272–3); 1875–76, *Martin* (1901 and 1923); 1915 to 1918, 1929, *Stone* (1935), *Stone and Ingerson*, (1934); end 1959, 1961, noted by author.

29. *Riñihue group*, which consists of *Choshuenco* 39°55′S 72°03′W, 2,300 meters, and *El Mocho* 39°56′S 72°02′W, 2,430 meters. The only report of activity is that recorded by *Vidal Gormaz* (1869), which was told by the Fathers of the Mission of Quinchilca in the course of an exploration made in 1869. According to this report the "Riñihue" erupted several days starting Nov. 1, 1864.
30. *Nilahue group* consists of *Carrán* 40°21′S 72°06′W, 300 meters, and *Riñinahue* 40°22′S 72°06′W, 306 meters. The Nilahue craters (about 100 meters elevation above the Nilahue river) erupted in two successive eruptions: Riñinahue, April 1907 and Carrán, July–August 1955 (figure 13), *Cofre Zuniga* (1956), *Leon and Polle* (1956). Hot springs observed around Carrán Jan. 1961.

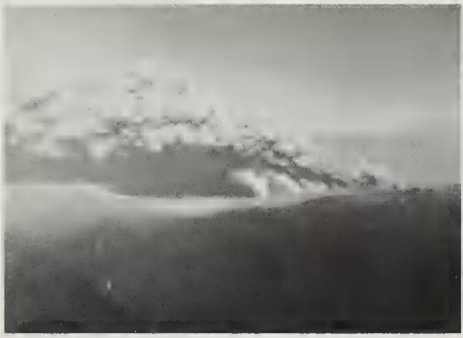

FIG. 14. Puyehue or Caulle or Cauye (No. 31), El. 2,240 m. The May 1960 eruption of Puyehue in connection with the great earthquake that devastated Valdivia, May 1960.

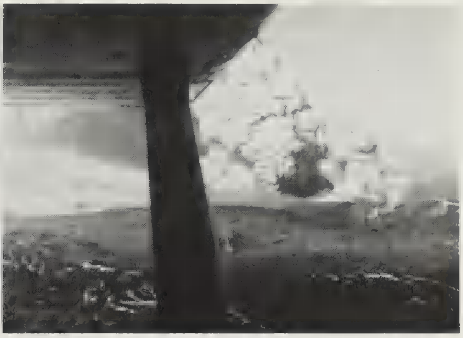

FIG. 15. Another View of the May 1960 Eruption of Puyehue. The eruption is coming from a fissure 300 meters long by 100 meters wide in the Las Azufreras area (sulfur mine area).

31. *Puyehue or Caulle or Cauye.* 40°35′S 72°08′W, 2,240 meters. (Includes *Las Azufreras.*) Reports of a major eruption of Puyehue in 1893 are considered doubtful by *Martin* (1895), who reported an eruption of Calbuco in 1893; however, Calbuco and Puyehue lie on the same fault and are known to erupt within a few years of each other or together. A lateral eruption of lava occurred in 1921 and early 1922 when a crater opened at Las Azufreras, an area of sulphur mines and fumaroles, on the northwest flank of Puyehue. The data given by *Krumm* (1923) on the 1921 Las Azufreras eruption are erroneous. *Brüggen* (1950) lists an eruption in 1919, which was probably the 1921 eruption. The Las Azufreras area of Puyehue erupted May 24, 1960 in connection with the catastrophic earthquake of May 1960, sending a cloud of ash and steam to a height of about 6,000 meters (figures 14 and 15). The ash and steam were emitted from a fissure 300 meters long by 100 meters wide for several weeks, and were followed by viscous lava, *Saint-Amand* (1961).
32. *Osorno.* 41°06′S 72°30′W, 2,660 meters (see figure 1). Osorno has an impressive but unprecise history of activity during the past centuries. *O'Compley* (1945)

mentions eruptions in 1575, 1640, and 1644 without citing any source. A search of the chronicles of the 16th and 17th centuries failed to reveal any mention of these eruptions; however, it should be noted that these same chronicles give detailed information on other cataclysms, such as the earthquake that destroyed Valdivia in 1575 and the eruption of Llaima in 1640. It should also be noted that *Rosales*, who has the most firsthand information on Southern Chile, makes no mention of the activity of Osorno during this period, nor does *de Ovalle*, although they both wrote about the 1640 eruption of Llaima, *de Ovalle* (1646); *Rosales* (1877). Osorno erupted in 1719 and continued active until 1790, *Fonck* (unpublished, cited by *Martin*, 1901). Erupted March 9, 1790, to Dec. 1797, *Moraleda y Montero* (1888). Erupted Jan. 20 to end Feb. 1835, *Darwin* (1840, p. 356). Some activity 1834, *Darwin* (1840, p. 336). Some activity Nov. 7, 1837, *Vidal Gormaz* (1883). Some activity, probably fumarolic, 1852, *Philippi* (1853). Thermal manifestations in crater at present.

33. *Calbuco.* 41°20′S 72°37′W, 2,015 meters (see figure 5). Calbuco has been confused with Osorno and Minchinmávida. Active 1837 and 1838, *Domeyko* (1850). Erupted Feb. 1893 to mid-1895, *Martin* (1895). Moderately active 1895 to April 1917, according to various reports. Erupted 1917, *Brüggen* (1950). No information is available on Calbuco from 1917 until 1929, *Brüggen* (1950), when a short and violent eruption occurred followed by a period of total inactivity. Totally inactive 1960. Violent eruption late Jan. 1961, starting with massive mud flows followed by the extrusion of two streams of andesitic lava.
34. *Huequi or Huequen.* 42°20′S 72°40′W, 1,050 meters. Erupted 1890, *Risopatron* (1924, p. 410); 1893, *Martin* (1895); *Maldonado and Gonzales* (1898); 1896, *Risopatron* (1924, p. 410). Erupted explosively 1906, *Martin* (1923); *Gutenberg and Richter* (1949); 1907, *Steffen* (1907); 1920, *Risopatron* (1924, p. 410). Reports of eruptions after 1893 are probably (author's opinion) exaggerated reports of minor activity.
35. *Minchinmávida.* 42°46′S 72°27′W, 2,470 meters. Minchinmávida is probably the Cuchucavi or Quechucabi of *de Ovalle* (1646) and the Cechucavi of *Molina* (1782). *Perrey* (1858) reports an eruption in 1742. According to *Steffen* (1944, p. 280) this would be the volcano that *Darwin* (1840, p. 336 and 346) referred to as "saddle topped", which he saw active Nov. 1834. *Darwin* (1840, p. 276), on the basis of information obtained from a letter by Mr. Douglas of Chiloe, describes an eruption of Minchinmávida in 1835.
36. *Corcovado.* 43°11′S 72°48′W, 2,300 meters. Active, Nov. 1834, *Darwin* (1840, p. 336 and 346). Erupted explosively Nov. 1835, *Darwin*, on the basis of information obtained from Mr. Douglas of Chiloe (1840, p. 356).
37. *Lautaro.* 49°01′S 73°33′W, 3,380 meters. There have been various reports since the middle of the 19th century regarding volcanic activity in the vicinity of the 49th parallel south. As a result of the Shipton expeditions in the summer of 1958–59, 1959–60, and 1960–61, it has been possible to attribute at least part of the activity to the highest peak of Cordon Pius XI. This peak has been reported as Cerro Piramide in the preliminary map of the Instituto Geografico Militar, and as Cerro Lautaro by *Lliboutry* (1956, p. 384 and 408). *Shipton* (1960) asserted that this peak of was a fully active volcano. Perhaps

activity observed from an aircraft of the Chilean Air Force in October 1961 can be attributed to this volcano, *Casertano* (1962).

38. *Mount Burney.* 52°20′S 72°24′W, 1,758 meters. Mount Burney is the southernmost volcano on the American Continent. The only known activity is an eruption in 1910, reported in Boletino del Servicio Sismologico de 1910, p. 69.

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THE FEBRUARY 1961 ERUPTION OF CALBUCO VOLCANO

By Erik Klohn

The eruption of Calbuco volcano, 2,015 meters above sea level, started on February 1, 1961. The author spent February 4 to 21 with Dr. Haroun Tazieff of UNESCO, Dr. Pierre Evrard of the Centre National de Vulcanologic de Belgie (CNV), and Dr. Lorenzo Casertano of the University of Chile.

Calbuco and the surrounding area are shown in figure 1 (in pocket at the back of this issue).

On the northeast flank of the volcano there are a few remnants of an older, somma-type volcano. The present Calbuco is in the old somma and is of the strato or composite type.

On January 25, the volcano began emitting columns of white clouds of water vapor. Series of earth tremors shook the windows of nearby houses.

At 5:00 a.m. on February 1, a lahar descended the flank and entered Lake Llanquihue, without any evidence of pyroclastic or explosive activity. We can hypothesize that the lahar started at 4:00 a.m. A little before noon of the same day, the first explosion was noted.

In total, the Calbuco eruption produced three lahars: (1) down the north flank to Lake Llanquihue, (2) down the south flank to Lake Chapo, (3) down the northeast flank to the Rio Petrohué.

The north-flank lahar was the largest and caused the most damage, for it covered cultivated fields. It was caused by the eruption of lava and pyroclastic material and the consequent melting of ice and snow. Descending the Rio Colorado channel to an altitude of 500 meters above sea level, where the channel was 100 meters wide and 12 meters deep, the lahar overflowed onto land of the Fundo Entreries. The estimated velocity of the lahar in the channel was 20 km/hr and its probable volume was 3,000 m^3/sec. Ten days later, the surface of the lahar was still steaming, and it was observed to be broken by numerous craters—produced by escaping steam—as much as 2 meters in diameter and some tens of centimeters high. The lahar covered the main highway 6 km south of Ensenada to a depth of 1.5 to 2 meters, but two days after the lahar flowed, it was well enough cemented for motor vehicles to pass over it. Judging from its appearance at the surface, the lahar was about 30% fresh lava.

The crater of the volcano has a diameter of about 1,500 meters, and the height of the rim is about 150 meters above the floor of the crater. During the last eruption, there were two active vents situated on a north-striking fracture near the east edge of the broad crater floor. Lava extruded from the north vent followed the upper course of the Rio Colorado lahar. Lava from the south vent domed the overlying ice and produced a system of concentric and radial fissures in the dome before it escaped and flowed into the Rio Blanco to the south (figure 2, lower left hand corner). The radial cracks were as much as 200 meters long.

The Rio Colorado lava stream flowed with a velocity of 4 m/hr, stopping at 560

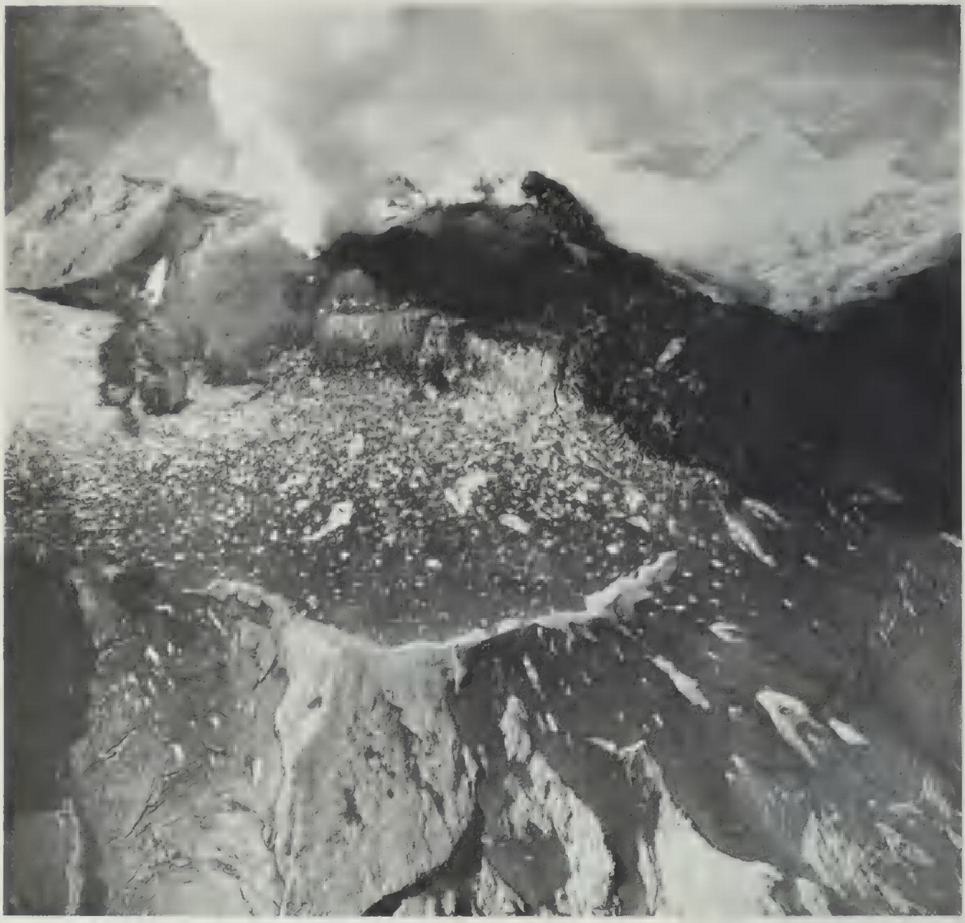

FIG. 2. Calbuco Volcano During Eruption. Note the radial fractures, covered by ashes, and the steam vent. Photo by Chilean Air Force.

meters above sea level on February 20. The Rio Blanco lava stream flowed only a few hundred meters.

Explosive activity was noted from the beginning of the eruptive stage. The explosive activity was expressed only by subterranean noises and columns of water vapor until March 10, at 6:00 a.m. when an exceptionally violent explosion that was heard as far away as 8 km was accompanied by an ash-charged, mushroom-shaped column that rose to 3,000 meters above the cone. According to T. Linz of Puerto Montt, bombs 3 meters in diameter were thrown as high as 500 meters. The ash was blown eastward, obscuring the sky as far as Peulla from 8:30 a.m. until noon, and blanketing that area with ash to a depth of a few millimeters.

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Bulletin of the Seismological Society of America. Vol. 53, No. 6, p. 1437. December, 1963

MINUTES OF THE SPECIAL MEETING OF THE SEISMOLOGICAL SOCIETY OF AMERICA

AUGUST 21, 1963

The Seismological Society of America held a special luncheon meeting on August 21, 1963 in the Dining Commons, University of California, Berkeley, California. Thirty-one members were in attendance.

After President Howell introduced the Society's officers and after he made announcements of general interest, he presented the following three resolutions to amend the Society's Articles of Incorporation:

RESOLVED: That Article SECOND of the Articles of Incorporation of this corporation be amended to read in full as follows:

> "(A). The specific and primary purposes for which this corporation is formed are to disseminate educational material and conduct research relating to earthquakes and allied phenomena, and to engage in other charitable, educational, and scientific activities."
>
> "(B). That the general purposes and powers are as permitted by law and that are necessary to, incidental to, or in furtherance of the specific and primary purposes."
>
> "(C). This corporation shall not, as a substantial part of its activities, carry on propaganda, or otherwise attempt, to influence legislation. This corporation shall not participate in, or intervene in (including the publishing or distributing of statements), any political campaign on behalf of any candidate for public office."

RESOLVED FURTHER: That Article THIRD of the Articles of Incorporation of this corporation be amended to read in full as follows:

> "This corporation is organized pursuant to the General Nonprofit Corporation Law of the State of California."

RESOLVED FURTHER: That Article SEVENTH of the Articles of Incorporation of this corporation be amended to read in full as follows:

> "This corporation is one which does not contemplate pecuniary gain or profit to the members thereof and it is organized solely for nonprofit purposes. Upon the winding up and dissolution of this corporation, after paying or adequately providing for the debts and obligations of the corporation, the remaining assets shall be distributed to a nonprofit fund, foundation or corporation, which is organized and operated exclusively for charitable, educational, religious and/or scientific purposes and which has established its tax-exempt status under Section (501) (3) of the Internal Revenue Code. If this corporation holds any assets on trust, such assets shall be disposed of in such manner as may be directed by decree of the superior court of the county in which this corporation's principal office is located, upon petition therefor by the Attorney General or by any person concerned in the liquidation."

The resolutions were unanimously passed. Since there was no further business to transact, the meeting was adjourned at 1:00 P.M.

KARL V. STEINBRUGGE
Secretary

Bulletin of the Seismological Society of America. Vol. 53, No. 6, p. 1439. December, 1963

MINUTES OF THE SPECIAL MEETING OF THE BOARD OF DIRECTORS OF THE SEISMOLOGICAL SOCIETY OF AMERICA

AUGUST 21, 1963

The Board of Directors of the Seismological Society of America met in special session in the Dining Commons of the University of California, Berkeley, California, on August 21, 1963. The meeting was called to order at 1:00 P.M. by President Benjamin F. Howell, Jr. Present were Directors Byerly, Benioff, Richter, Hodgson, Wilson, Oliver, Steinbrugge, Murphy, Stauder, S.J., and Howell.

Three resolutions to amend the Society's Articles of Incorporation were unanimously passed. The exact wording may be found in the Minutes of the Membership's Special Meeting of August 21, 1963 (see elsewhere in this *Bulletin*).

The Board approved the action of the Society's officers in establishing, in the Society's name, a savings account with the Home Mutual Savings and Loan Association.

It was announced that the next regular meeting of the Society would be held on the University of Washington campus in Seattle on March 27 and 28, 1964. Further details will be found in the *Bulletin*.

The February, 1963 issue of the *Bulletin*, which was a special issue devoted to the engineering aspects of the 1960 Chilean Earthquakes, went out of print shortly after publication. The Executive Committee authorized a reprint edition which at this date is about two-thirds sold.

President Howell announced that Wm. Mansfield Adams, the Society's Editor, had donated the royalties of his forthcoming book "Earthquakes: An Introduction to Observational Seismology" to the Society for a period of ten years. It was stipulated in the agreement between Adams and the Society that the royalties be placed in a fund to be designated "Fund for *Direct* Exploration." The sole purpose of the fund is to defray publication costs in connection with papers dealing with the direct exploration of the Earth or other planets.

The status of the 52 year index was reviewed by Steinbrugge and by Adams. Adams submitted a prototype of the "Keyword-in-Context" Index for the Board's inspection and he briefly discussed the progress and future plans. The Board approved the work accomplished to date.

The meeting was adjourned at 1:30 P.M.

Karl V. Steinbrugge
Secretary

ANNOUNCEMENT OF THE ANNUAL MEETING OF THE SEISMOLOGICAL SOCIETY OF AMERICA

The annual meeting of the Seismological Society of America will be held on Friday and Saturday, March 27 and 28, 1964 on the campus of the University of Washington, Seattle, Washington, in conjunction with that of the Cordilleran Section of the Geological Society of America. Sessions may be scheduled for Thursday if the volume of papers require additional sessions. Those who wish to present papers should have titles and abstracts (in triplicate) of not more than 250 words in the hands of the Secretary by January 10, 1964.

Karl V. Steinbrugge
Secretary

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GUIDELINES FOR POTENTIAL CONTRIBUTORS TO THE BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA

To permit fast publication, a contributor should:

1. Include an informative abstract.
2. Eliminate all footnotes by incorporating them into the text.
3. Include the complete title in each reference. In the text, cite a reference by author's name with the year of publication included in parentheses.
4. Have a colleague read the manuscript thoroughly and critically. Attend to his admonishments.

In general:

1. Do not submit material of a quality lower than that of the articles you read.
2. Read over your own manuscript several times.
3. A report on contract- or grant-sponsored work should be shortened. Such a report is usually much longer than the corresponding article need be.
4. Keep at least one copy of the material submitted.

Submit one master complete with original figures, preferably with two complete copies to expedite review, to:

Wm. Mansfield Adams, Editor
Bulletin of the Seismological Society of America
Planetary Sciences Inc.
P.O. Box 561
Santa Clara, California

Upon receipt of your article, an acknowledgment card will be mailed.

If your article is accepted, you will receive an acceptance letter, sometimes with constructive criticism.

You will receive page proofs—not galley proofs. Therefore, no significant revisions can be made unless the costs are borne by the author or his organization.

A reasonable goal from time of submission to date of publication is four months.

If these guidelines are followed, the author can be assured of the cooperation of the reviewers and the Editorial Committee.

Wm. Mansfield Adams, Editor

ANNUAL INDEX FOR VOLUME 53

By Nancy L. Nuhn

The Annual Index for Volume 53 (Numbers 1 through 6) of the *Bulletin* of the Seismological Society demonstrates the Keyword-in-Context Index principle. This same indexing principle is to be used for the 53-year Cumulative Index of the Seismological Society of America under the provisions of a grant from the National Science Foundation. The Annual Index that is presented on the following pages was used as a test problem for the more comprehensive 53-year Cumulative Index of the *Bulletin.*

The Keyword-in-Context Index is composed of three indices: the keyword index; a bibliography; and an author index. The keyword index utilizes the keyword-in-context principle, by which certain keywords, together with surrounding words that act as modifiers, are selected from the titles of the publications. These keywords serve as index entries from each title. There will be as many index entries generated as there are keywords contained on the title cards. The keywords and their modifiers are followed by a reference code comprised of the first four letters of the senior author's last name, two initials, the year of publication, and the first letter from the first three significant words of the title of the article. The same reference code is used with the alphabetized author index and bibliography.

How to Use the Index

Your subject is found in the alphabetized listing in column 25. This listing starts on the next page. The remainder of the title that includes the subject precedes or follows on the same line. In the column on the right is each title's "Index Code", referring you to the Bibliography. As a trivial example, to find the annual Index: "Annual" is found in the listing on the next page: NLN IB-63-AI is its Index Code, locating it in the Bibliography. On page 1456 you find the author, (abbreviation for Nancy L. Nuhn plus IBM7094), title and page.

The author, NLN IBM7094, is listed alphabetically in the Author Index (page 1459) with the same Index Code (NLN IB-63-AI).

KEY WORD IN CONTEXT

RECONSTRUCTED TITLE		INDEX CODE
OSEISMS WITH PERIODS OF	ABOUT 27 SECONDS,, ADDITIONAL EVIDEN	OLIVJ -63-AER
ERAL CHARACTERISTICS OF	ACTIVE ANDEAN VOLCANOES AND A SUMMAR	CASEL -63-GCA
AND A SUMMARY OF THEIR	ACTIVITIES DURING RECENT CENTURIES	CASEL -63-GCA
C SURFACE WAVES. 3. THE	ALASKA EARTHQUAKE OF JULY 10, 1958	BENMA -63-SSL
NORTH-PACIFIC, PART II.*	ALEUTIAN ISLANDS S-WAVE STUDIES OF E	STAUW -63-SSE
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CAL SOCIETY OF AMERICA,	AUGUST 21, 1963 MINUTES OF THE SPECI	STEIKV-63-MSM
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ALSOP LE	ALSOLE-63-FSV
ALTERMAN Z	PEKECL-63-PSP
ALVAREZ L	ALVAL -63-SMB
ALVERSON RC	ALVERC-63-UEM
AMBRASEYS NN	AMBRNN-63-BIE
AMBRASEYS NN	AMBRNN-63-SSG
ARIAS A	ARIAA -63-DEA
BAKER CD	BERGJW-63-OET
BARROS G	SIEVHA-63-SSW
BATH M	SANTTA-63-CSP
BEN-MENAHEM A	BENMA -63-SSL
BEN-MENAHEM A	TOKSMN-63-VML
BENIOFF H	BENIH -63-SWF
BERG JW	BERGJW-63-OET
BLUME JA	BLUMJA-63-SAS
BOLLINGER G	STAUW -63-PVO
BOWES W	DOBRE -63-RBG
BOWES W	THOMH -63-EEM
BOWES W	THOMH -63-FOM
BOWES W	THOMH -63-GRE
BOWES W	THOMH -63-GRE
BRAVO N	DOBRE -63-RBG
BRAVO N	THOMH -63-EEM
BRAVO N	THOMH -63-FOM
BRAVO N	THOMH -63-GRE
BRAVO N	THOMH -63-GRE
BRUNE J	BRUNJ -63-SWE
CASERTANO L	CASEL -63-GCA
CHINNERY MA	CHINMA-63-SCT
CHOWDHURY DK	CHOWDK-63-EWP
CISTERNAS A	CISTA -63-PDF
CLOUD WK	CLOUWK-63-PMS
CLOUGH RW	CLOURW-63-EDB
CLOUGH RW	CLOURW-63-RDE
CONNELL DV	WILLPL-63-NSS
COOK KL	COSTJK-63-AEP
COSTAIN JK	COSTJK-63-AEP
COX DC	COX DC-63-TMH
DAVIS SN	DAVISN-63-LLR
DEHLINGER P	CHOWDK-63-EWP
DENOYER J	DENOJ -63-MVC
DENOYER J	WILLDE-63-DEU
DERESIEWICZ H	DEREH -63-UDP
DOBROVOLNY E	DOBRE -63-RBG
DORMAN J	BRUNJ -63-SWE
DOYEL WW	DOYEWW-63-RBG
DUKE CM	DUKECM-63-RSF
DUTTA S	DUTTS -63-RWT
DYK K	DYK K -63-BDG
EVISON FF	EVISFF-63-EFC
EWING JI	PRENDD-63-SMD
FALCON E	DOYEWW-63-RBG
FARA HD	FARAHD-63-EMS
FLORES R	STEIKV-63-SEV
FRANTTI GE	FRANGE-63-ESU
FRANTTI GE	FRANGE-63-SED
GAIR FC	ALVERC-63-UEM
GALLI C	GALLC -63-EEM
GALLI C	GALLC -63-RBG
GALLI C	GALLC -63-RBG
HALES AL	HARKDG-63-DSL
HARKRIDER DG	HARKDG-63-DSL
HASBRICH RA	HASBRA-63-CSM
HASKELL NA	HASKNA-63-RPR
HJORTENBERG E	HJORE -63-STM
HOOK JF	ALVERC-63-UEM
HOOK JF	KARLT -63-LPI
HOUSNER GW	HOUSGW-63-BIP
HOUSNER GW	HOUSGW-63-DBW
HOUSNER GW	HOUSGW-63-PER
HOWELL BF	LAVIPM-63-MSE
HOY RB	HOY RB-63-IFU
HUANG YT	HUANYT-63-ASN
HUDSON DE	HUDSDE-63-MGM
HUSID R	ARIAA -63-DEA
INGRAM RE	INGRRE-63-FMC
JACKSON PL	JACKPL-63-SET
JENSCHKE VA	CLOURW-63-EDB
KARLSSON T	KARLT -63-LPI
KARZULOVIC J	DAVISN-63-LLR
KASAHARA K	KASAK -63-CPF
KASAHARA K	KASAK -63-RMS
KEYS JG	KEYSJG-63-TMS
KLOHN E	KLOHE -63-FEC
LAVIN PM	LAVIPM-63-MSE
LEEDS DJ	DUKECM-63-RSF
LEMKE R	DOBRE -63-RBG
LOCK MH	LOCKMH-63-ASE
MACCARTHY GR	MACCGR-63-TFE
MELLA A	WRIGC -63-MSP
MINK JF	COX DC-63-TMH
MITRA M	MITRM -63-SSH
MORAGA A	DOYEWW-63-RBG
MORAGA A	THOMH -63-EEM
MUNK WH	HASBRA-63-CSM
NLN+IBM7094	NLN IB-63-AI
NORTHRUP J	NORTJ -63-SFS
OLIVER J	OLIVJ -63-AER
OLIVER J	OLIVJ -63-CSL
PAGE R	OLIVJ -63-CSL
PEKERIS CL	PEKECL-63-PSP
PHINNEY RA	PHINRA-63-PSD
POLLACK H	DENOJ -63-MVC
POLLACK HN	POLLHN-63-ESS
POMEROY PW	POMEPW-63-LPS
PRENTISS DD	PRENDD-63-SMD
PRESS F	HARKDG-63-DSL
RAITT RW	NORTJ -63-SFS
ROMBERG FE	ROMBFE-63-AET
SAINT-AMAND P	SAINP -63-PCE
SANCHEZ J	GALLC -63-EEM
SANCHEZ J	GALLC -63-RBG
SANCHEZ J	GALLC -63-RBG
SANTO TA	SANTTA-63-CSP
SCHEIDEGGER AE	FARAHD-63-EMS
SIEVERS HA	SIEVHA-63-SSW
SKALAK R	DEREH -63-UDP
SMITH SW	PHINRA-63-PSD
SNODGRASS FE	HASBRA-63-CSM
STAUDER W	STAUW -63-PVO
STAUDER W	STAUW -63-SSE
STEINBRUGGE KV	STEIKV-63-AAM
STEINBRUGGE KV	STEIKV-63-MSM

STEINBRUGGE KV	STEIKV-63-MSM
STEINBRUGGE KV	STEIKV-63-SEV
THOMAS H	DOBRE -63-RBG
THOMAS H	THOMH -63-EEM
THOMAS H	THOMH -63-FOM
THOMAS H	THOMH -63-GRE
THOMAS H	THOMH -63-GRE
TOKSOZ MN	BENMA -63-SSL
TOKSOZ MN	TOKSMN-63-VML
UDIAS A	STAUW -63-SSE
VILLEGAS G	SIEVHA-63-SSW
VITOUSEK MJ	VITOMJ-63-TMF
WEISCHET W	WEISW -63-DDC
WEISCHET W	WEISW -63-FOG
WILLIS DE	WILLDE-63-CSW
WILLIS DE	WILLDE-63-DEU
WILLIS DE	WILLDE-63-NER
WILLIS DE	WILLDE-63-SML
WILLMORE PL	WILLPL-63-NSS
WILSON JT	WILLDE-63-DEU
WRIGHT C	WRIGC -63-MSP

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sheet 1

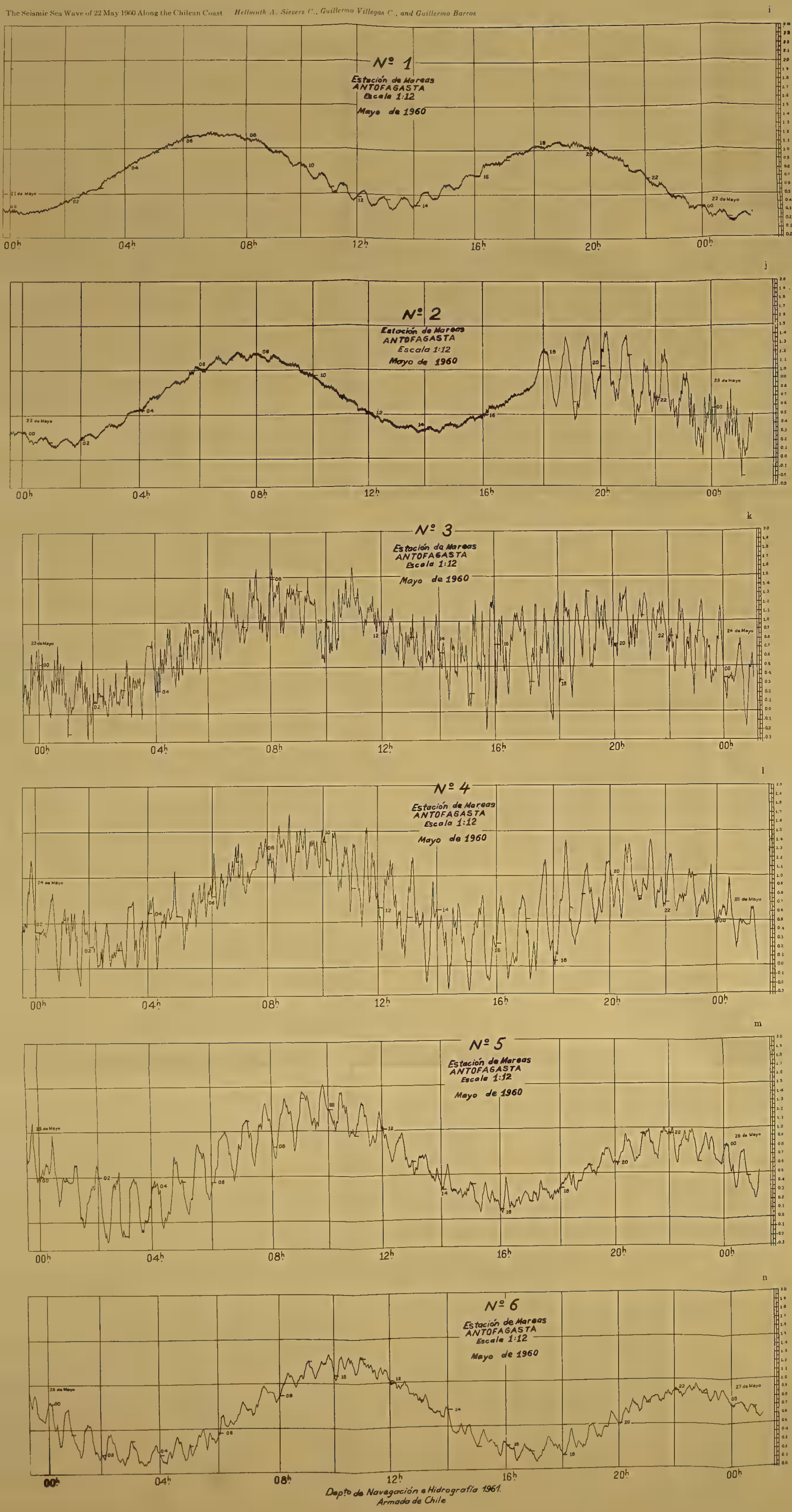

Fig. 1. (i)–(n) Tidegram from Antofagasta.

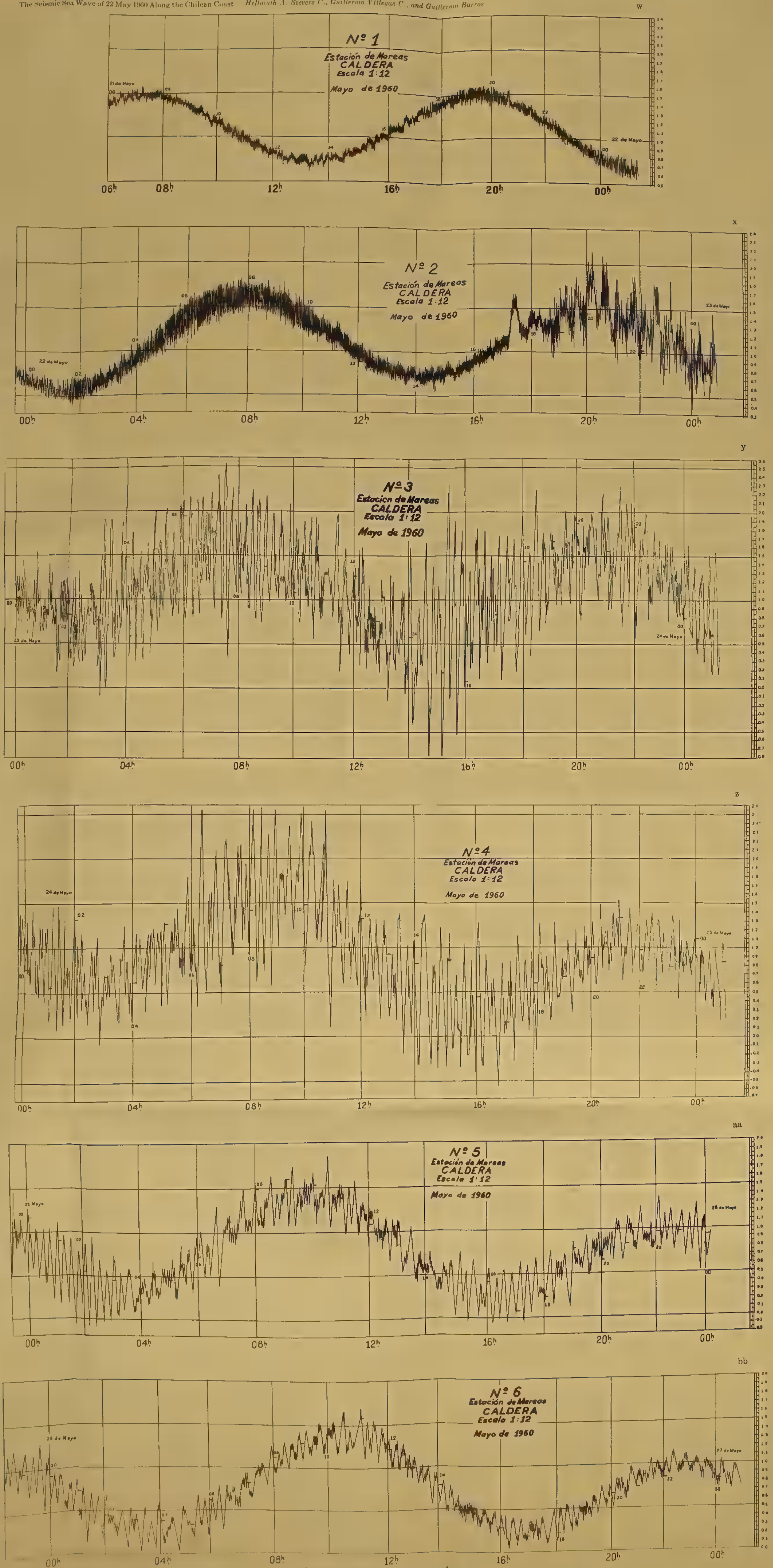

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Fig. 1. (w)–(bb) Tidegram from Caldera.

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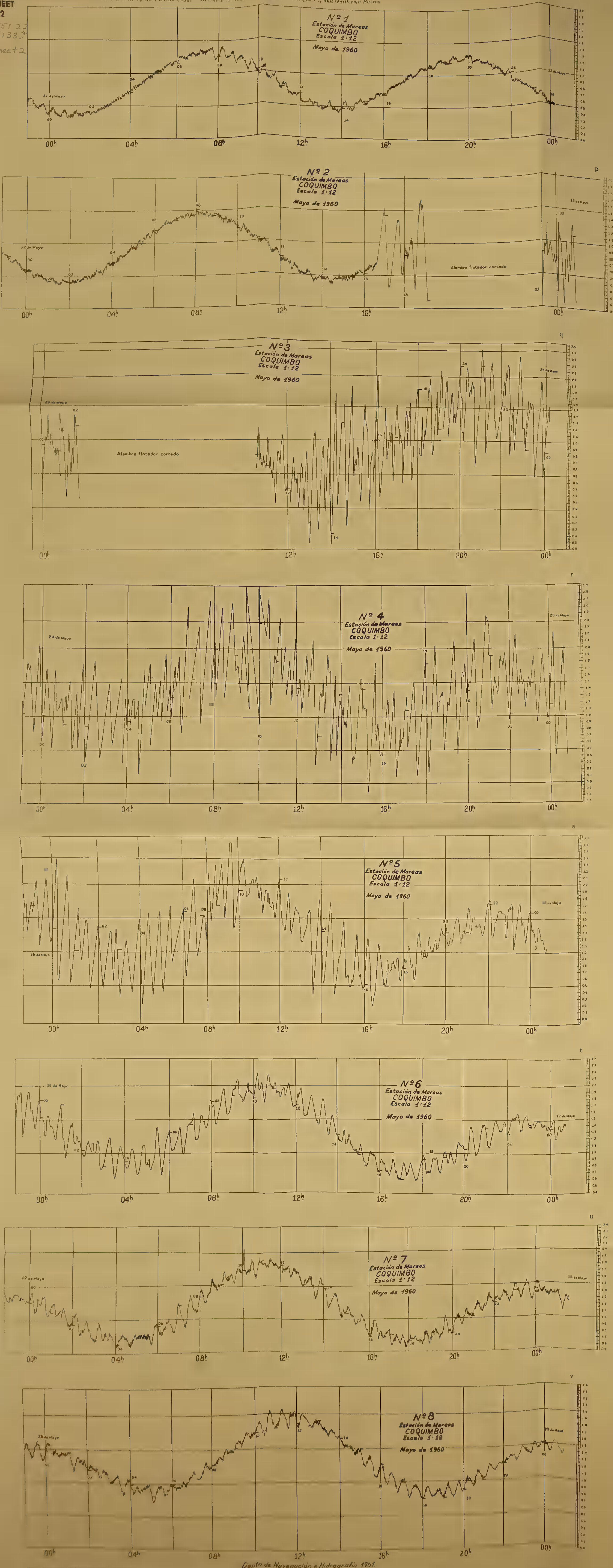

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Fig. 1 (o)-(v) Tidegram from Coquimbo.

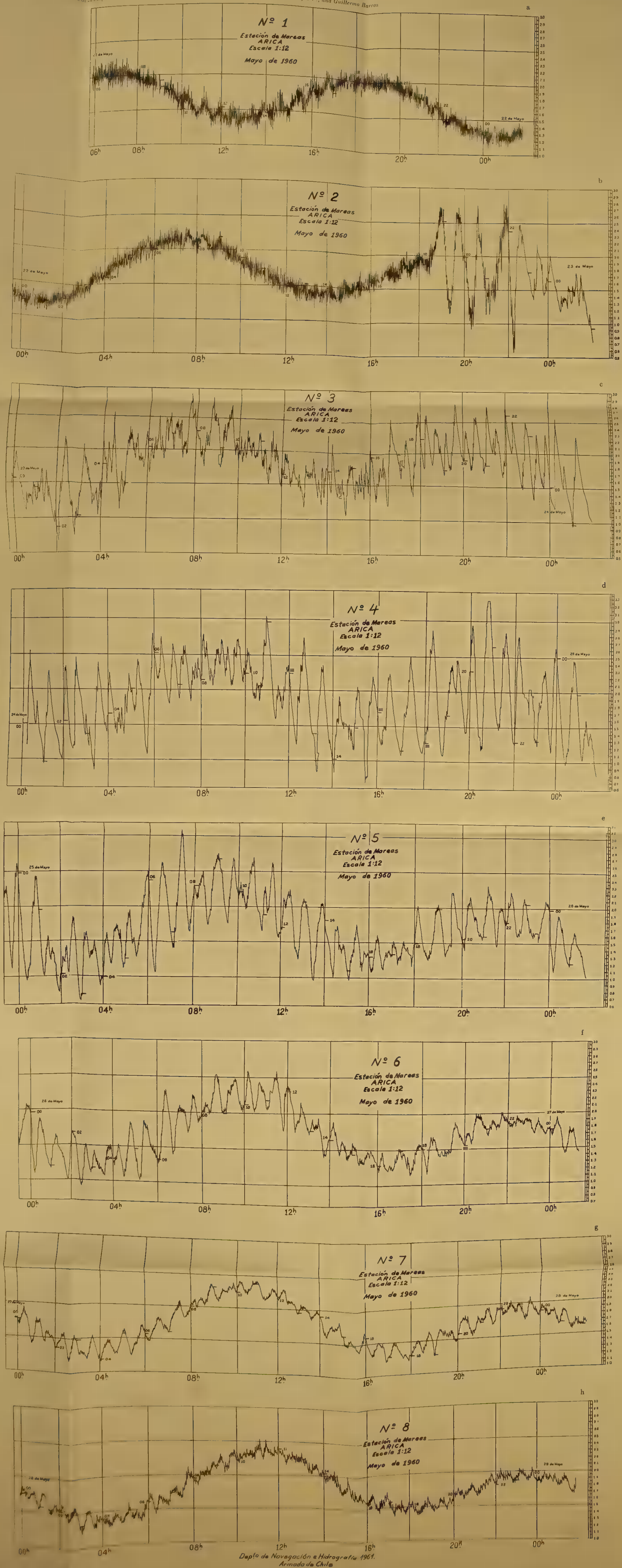

Fig. 1 (a)–(h) Tidegrams from Arica

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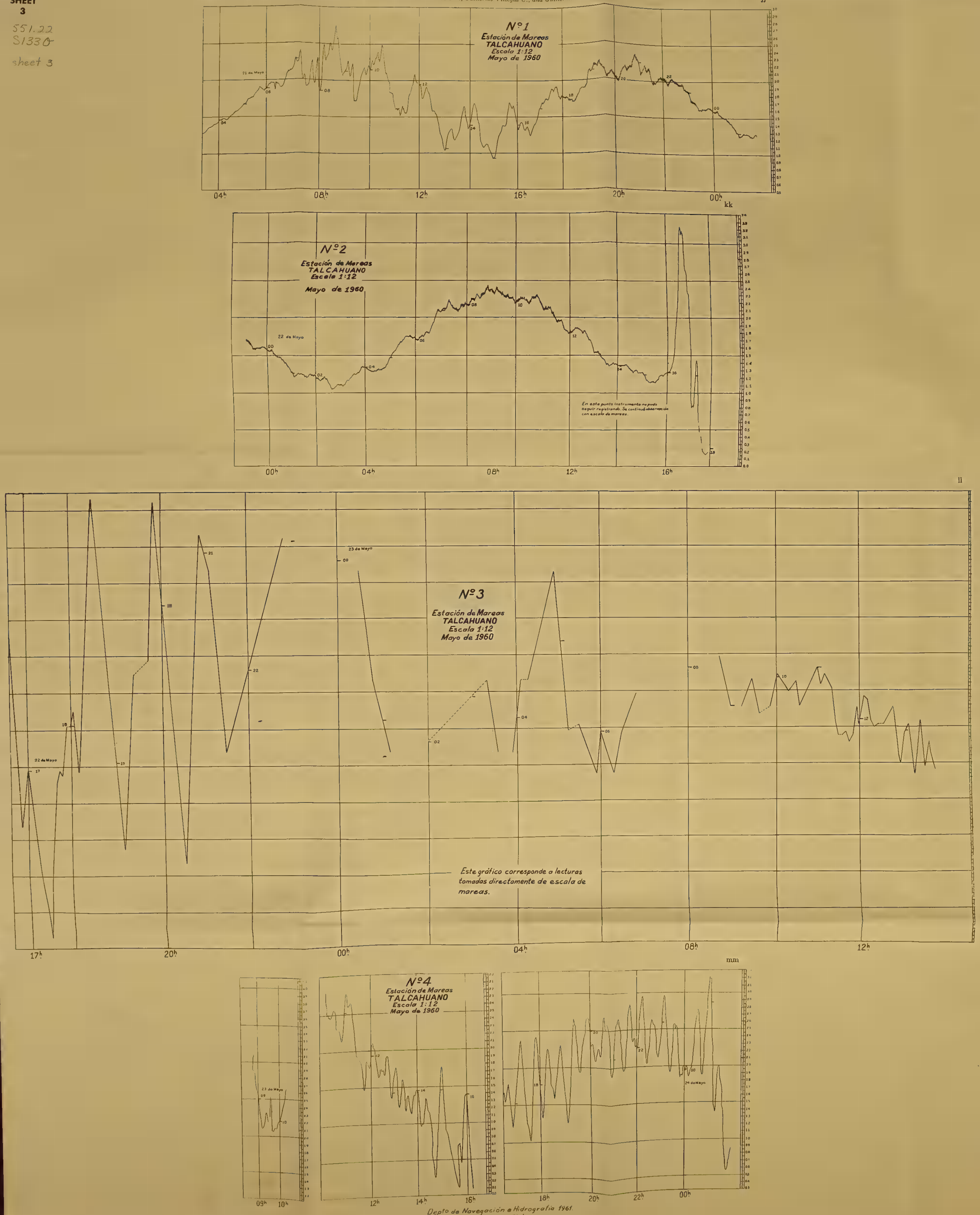

Fig. 1. (jj), (kk) Tidegram from Talcahuano from Tide Gage. (ll) (mm) Tidegram from Talcahuano Road on Tide Scale.

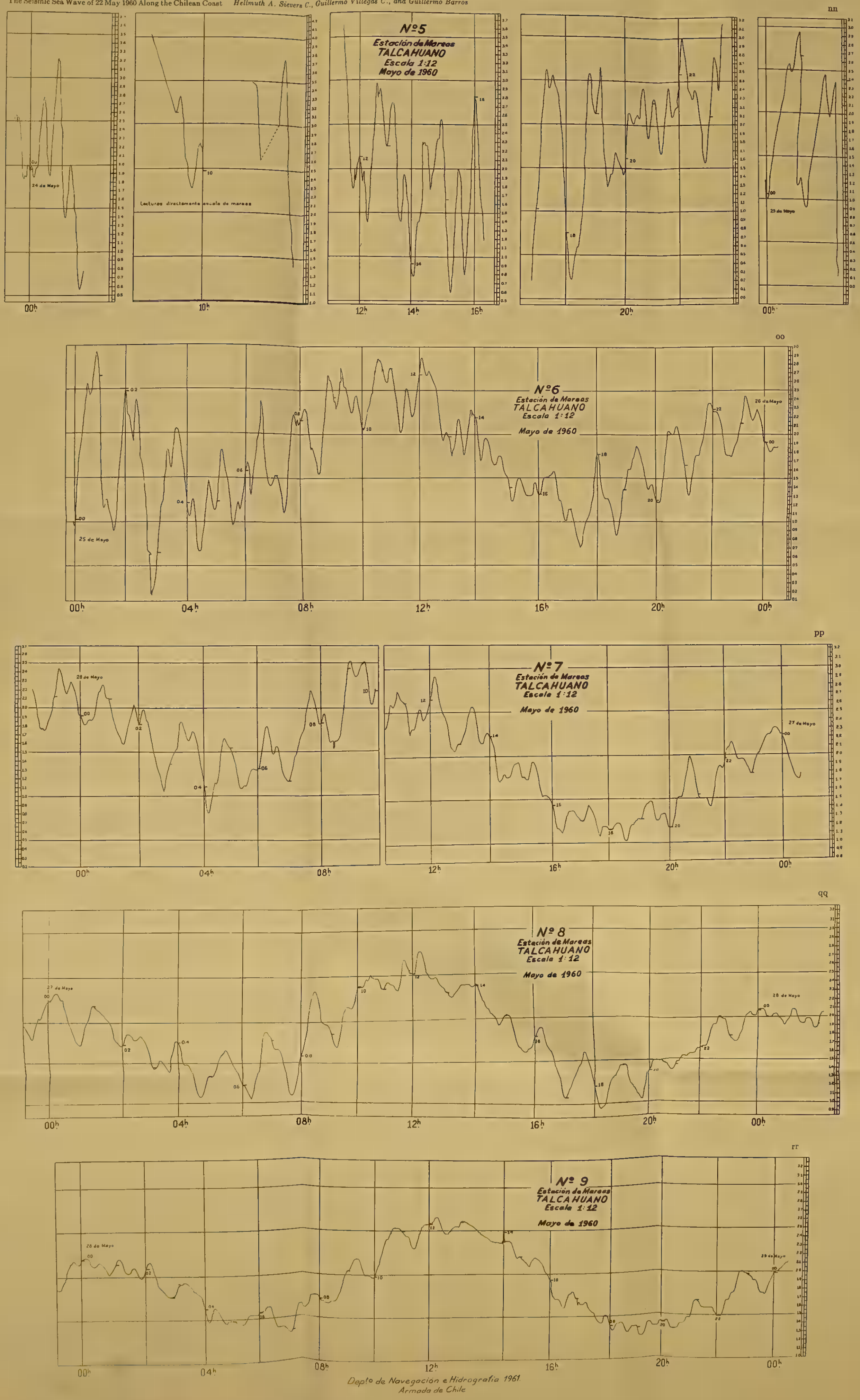

Fig. 1. (nn) Tidegram from Talcahuano Read on Tide Scale. (oo)–(rr) Tidegram from Talcahuano from Tide Gage.

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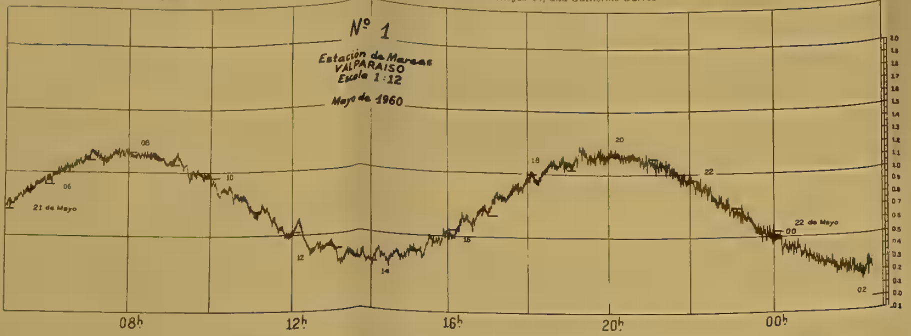

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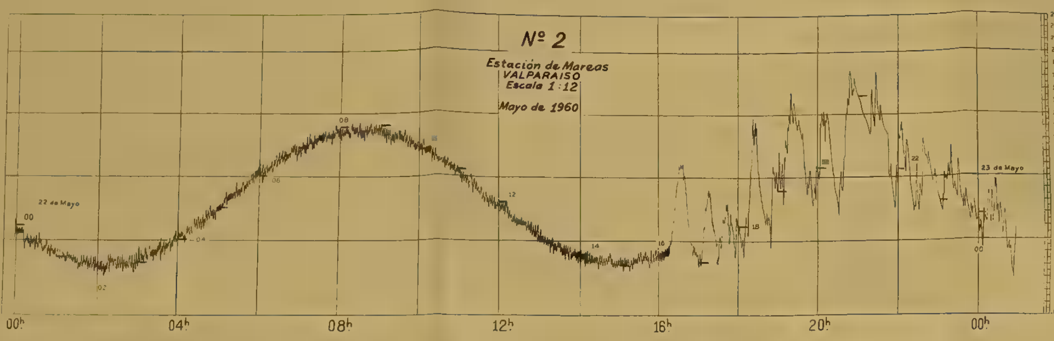

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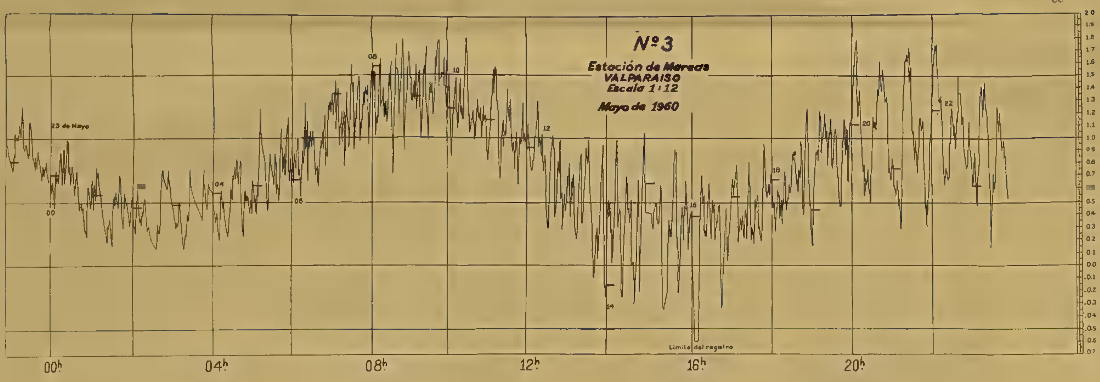

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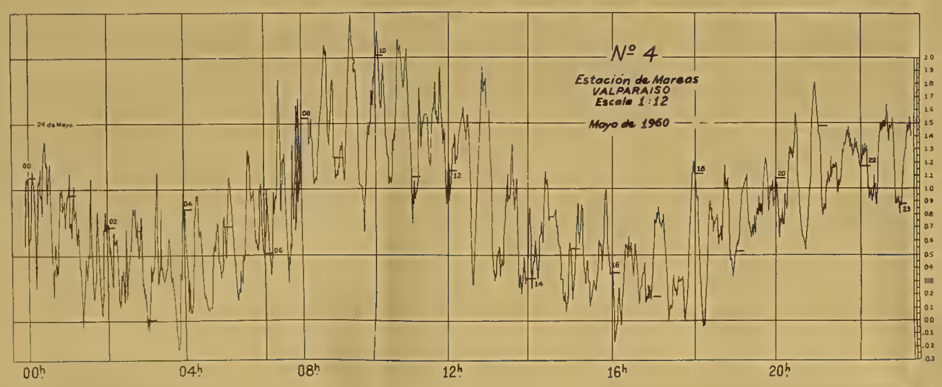

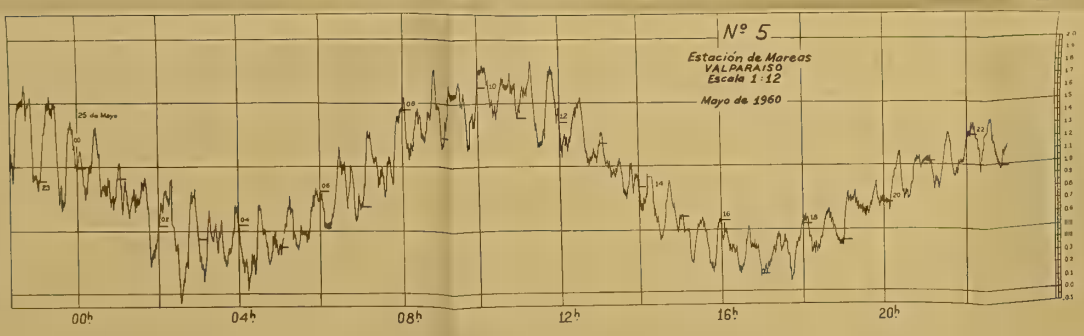

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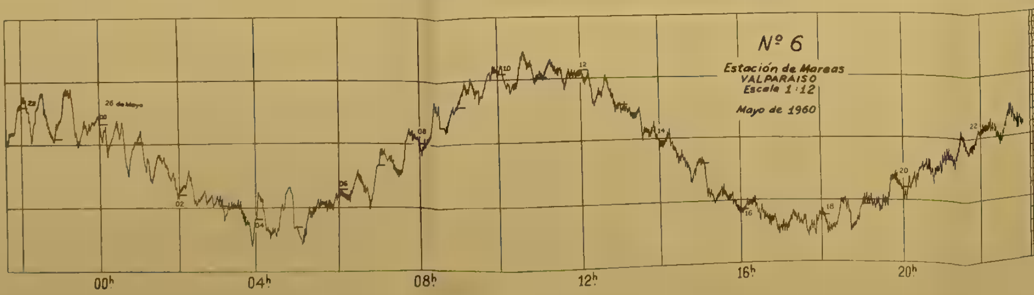

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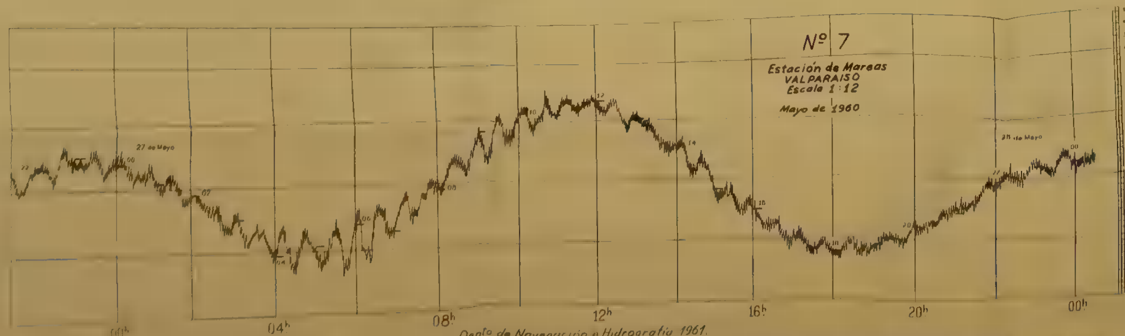

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[illegible] from Valparaiso.

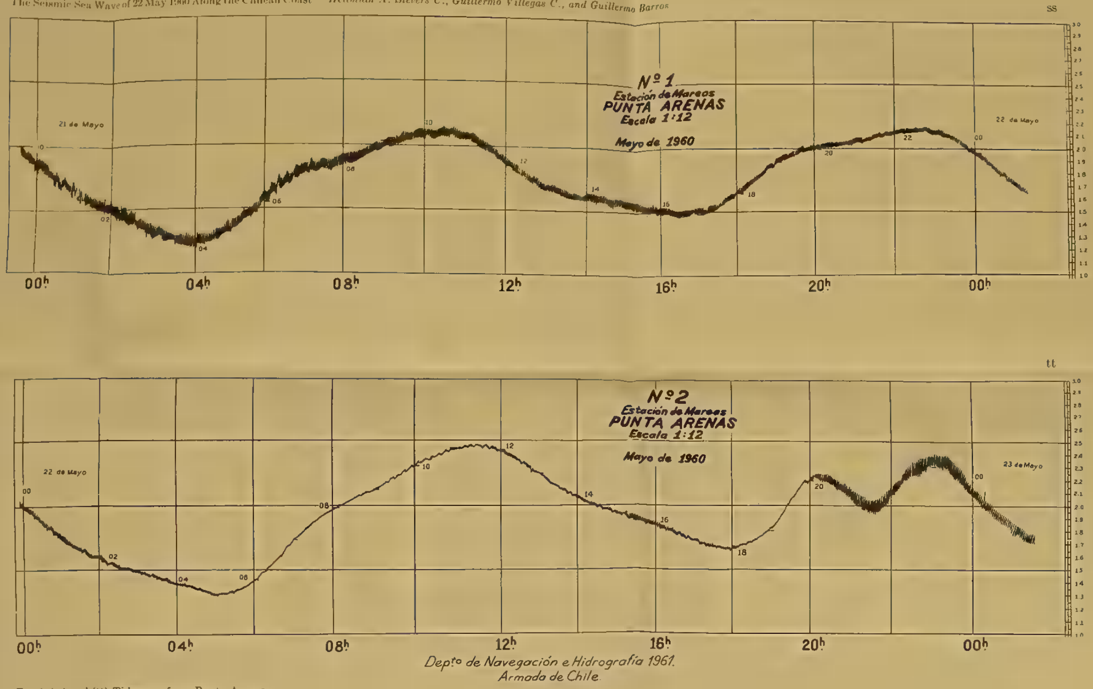

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Fig. 1. (ss) and (tt) Tidegram from Punta Arenas.

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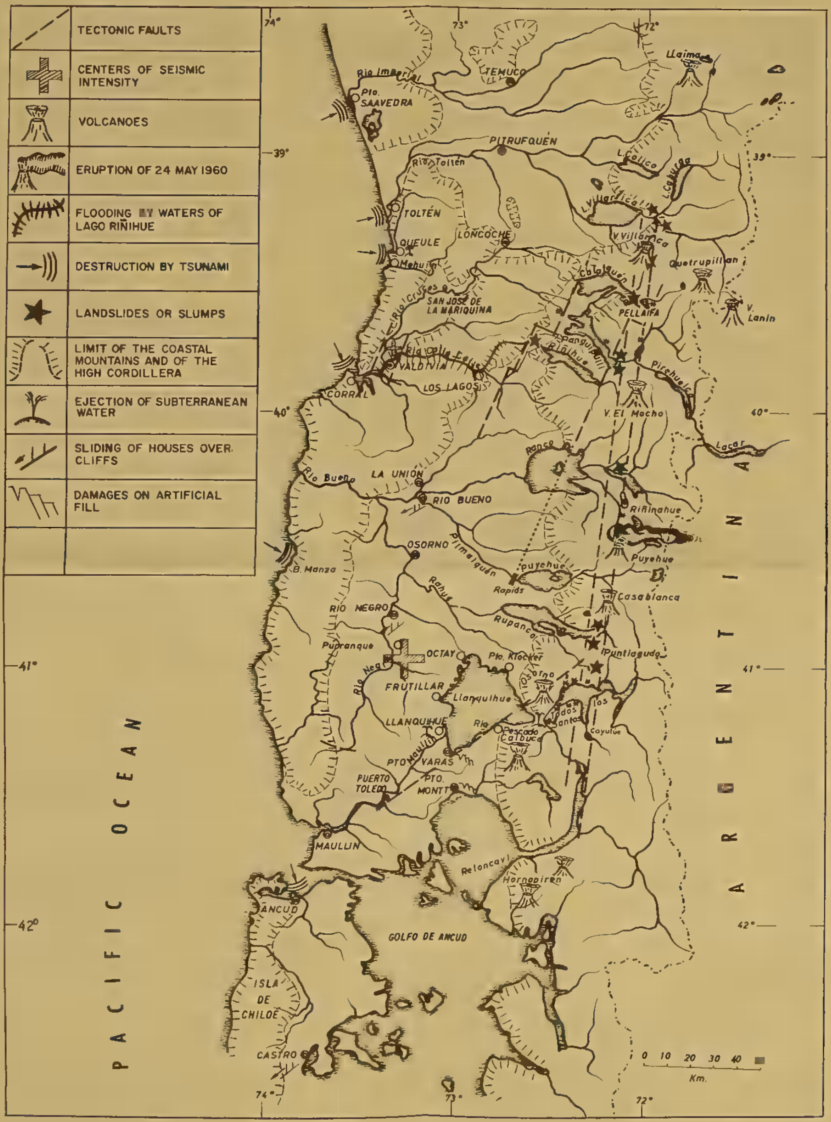

Fig. 1. Zone Between the Provinces of Cautin and Chiloé, Chile, Affected by the Earthquake of 22 May 1960.

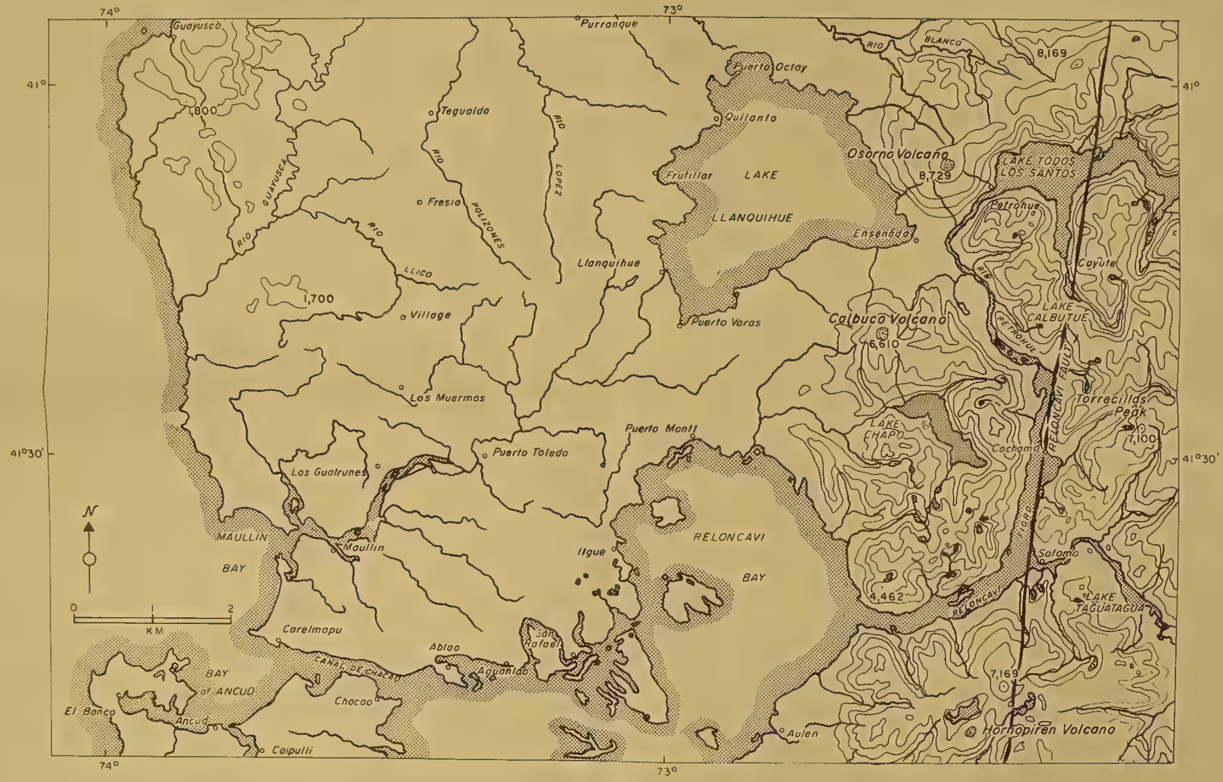

FIG. 1. Map of Calbuco and Environs.

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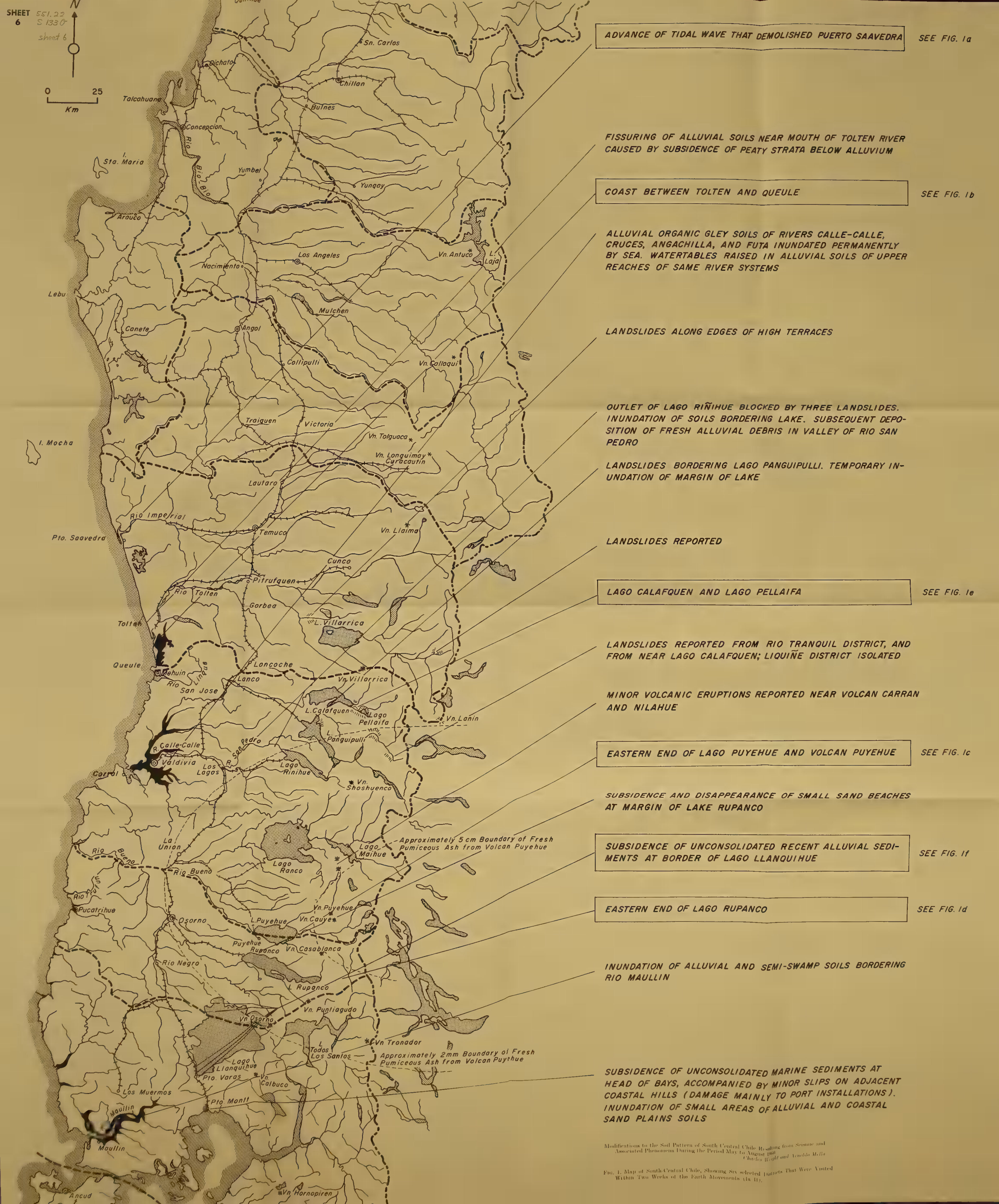
N
0
25
Km
ADVANCE OF TIDAL WAVE THAT DEMOLISHED PUERTO SAAVEDRA
SEE FIG. 1a
FISSURING OF ALLUVIAL SOILS NEAR MOUTH OF TOLTEN RIVER CAUSED BY SUBSIDENCE OF PEATY STRATA BELOW ALLUVIUM
COAST BETWEEN TOLTEN AND QUEULE
SEE FIG. 1b
ALLUVIAL ORGANIC GLEY SOILS OF RIVERS CALLE-CALLE, CRUCES, ANGACHILLA, AND FUTA INUNDATED PERMANENTLY BY SEA. WATERTABLES RAISED IN ALLUVIAL SOILS OF UPPER REACHES OF SAME RIVER SYSTEMS
LANDSLIDES ALONG EDGES OF HIGH TERRACES
OUTLET OF LAGO RIÑIHUE BLOCKED BY THREE LANDSLIDES. INUNDATION OF SOILS BORDERING LAKE. SUBSEQUENT DEPOSITION OF FRESH ALLUVIAL DEBRIS IN VALLEY OF RIO SAN PEDRO
LANDSLIDES BORDERING LAGO PANGUIPULLI. TEMPORARY INUNDATION OF MARGIN OF LAKE
LANDSLIDES REPORTED
LAGO CALAFQUEN AND LAGO PELLAIFA
SEE FIG. 1e
LANDSLIDES REPORTED FROM RIO TRANQUIL DISTRICT, AND FROM NEAR LAGO CALAFQUEN; LIQUIÑE DISTRICT ISOLATED
MINOR VOLCANIC ERUPTIONS REPORTED NEAR VOLCAN CARRAN AND NILAHUE
EASTERN END OF LAGO PUYEHUE AND VOLCAN PUYEHUE
SEE FIG. 1c
SUBSIDENCE AND DISAPPEARANCE OF SMALL SAND BEACHES AT MARGIN OF LAKE RUPANCO
SUBSIDENCE OF UNCONSOLIDATED RECENT ALLUVIAL SEDIMENTS AT BORDER OF LAGO LLANQUIHUE
SEE FIG. 1f
EASTERN END OF LAGO RUPANCO
SEE FIG. 1d
INUNDATION OF ALLUVIAL AND SEMI-SWAMP SOILS BORDERING RIO MAULLIN
SUBSIDENCE OF UNCONSOLIDATED MARINE SEDIMENTS AT HEAD OF BAYS, ACCOMPANIED BY MINOR SLIPS ON ADJACENT COASTAL HILLS (DAMAGE MAINLY TO PORT INSTALLATIONS). INUNDATION OF SMALL AREAS OF ALLUVIAL AND COASTAL SAND PLAINS SOILS
Sn. Carlos
Dichato
Chillan
Talcahuano
Bulnes
Concepcion
Rio Bio-Bio
I. Sta. Maria
Yumbel
Yungay
Arauco
Los Angeles
Vn. Antuco
L. Laja
Nacimiento
Lebu
Mulchen
Canete
Angol
Collipulli
Vn. Callaqui
Traiguen
Victoria
I. Mocha
Vn. Tolguaca
Vn. Longuimay
Curacautin
Lautaro
Rio Imperial
Pto. Saavedra
Temuco
Vn. Llaima
Cunco
Pitrufquen
Rio Tolten
Gorbea
Tolten
L. Villarrica
Queule
Mehuin
Rio Lingue
Loncoche
Lanco
Rio San Jose
Vn. Villarrica
L. Calafquen
Lago Pellaifa
Vn. Lanin
L. Panguipulli
R. Calle-Calle
Valdivia
Los Lagos
R. San Pedro
Lago Riñihue
Corral
Vn. Shoshuenco
La Union
Rio Bueno
Lago Ranco
Lago Maihue
Approximately 5 cm Boundary of Fresh Pumiceous Ash from Volcan Puyehue
Rio Bueno
Rio Tranque
Pucatrihue
Vn. Puyehue
L. Puyehue
Vn. Cauye
Osorno
Puyehue
Rupanco
Vn. Casablanca
Rio Negro
L. Rupanco
Vn. Puntiagudo
Vn. Osorno
Vn Tronador
L. Todos Los Santos
Approximately 2mm Boundary of Fresh Pumiceous Ash from Volcan Puythue
Lago Llanquihue
Pto. Varas
Vn. Calbuco
Los Muermos
Pto. Montt
Maullin
Ancud
Vn Hornopiren

Modifications to the Soil Pattern of South Central Chile Resulting from Seismic and Associated Phenomena During the Period May to August 1960
Charles Wright and Arnoldo Mella

FIG. 1. Map of South-Central Chile, Showing Six selected Districts That Were Visited Within Two Weeks of the Earth Movements (1a 1f).

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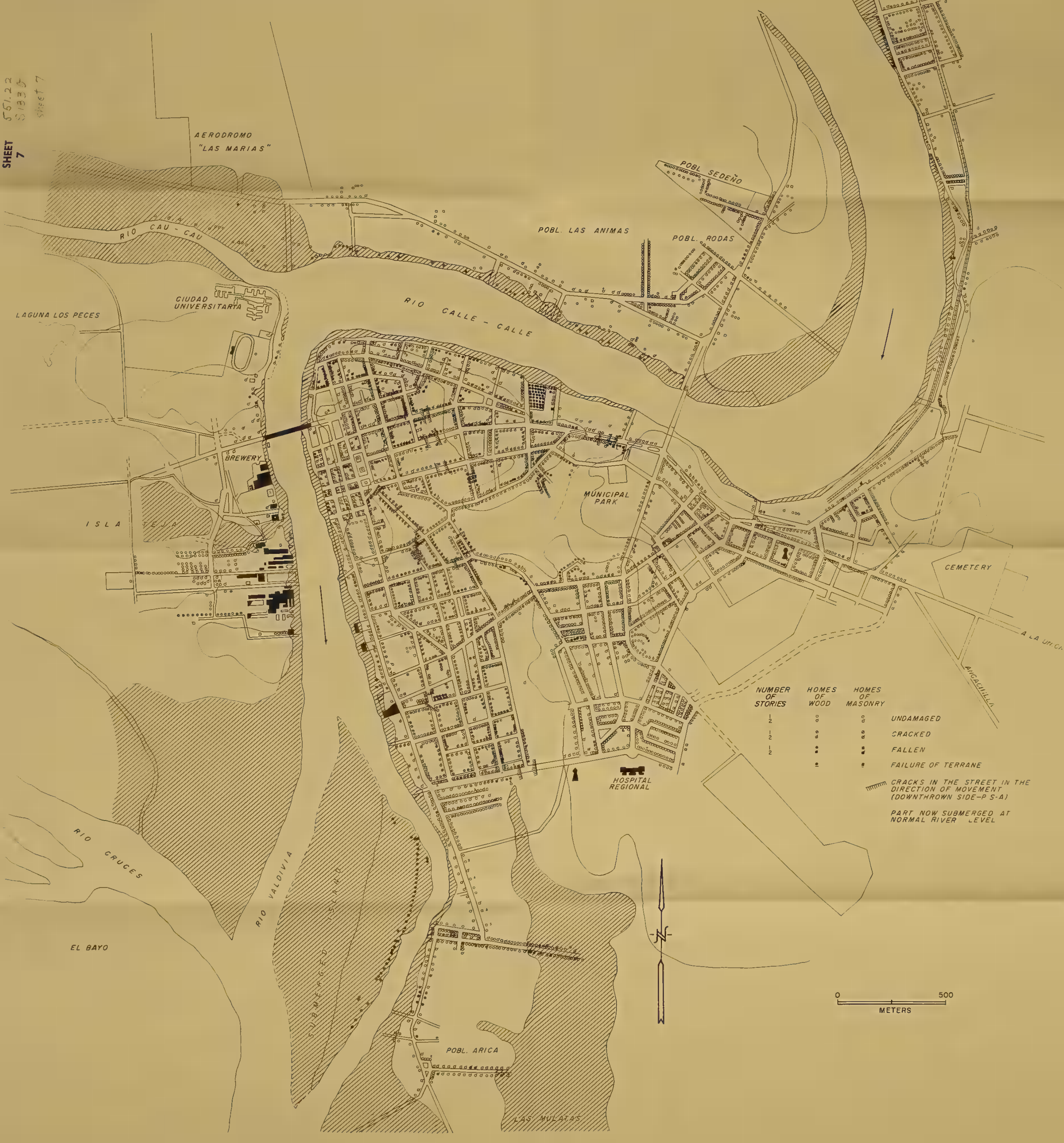

FIG. 1 Map of Valdivia with Indications of Earthquake Damage

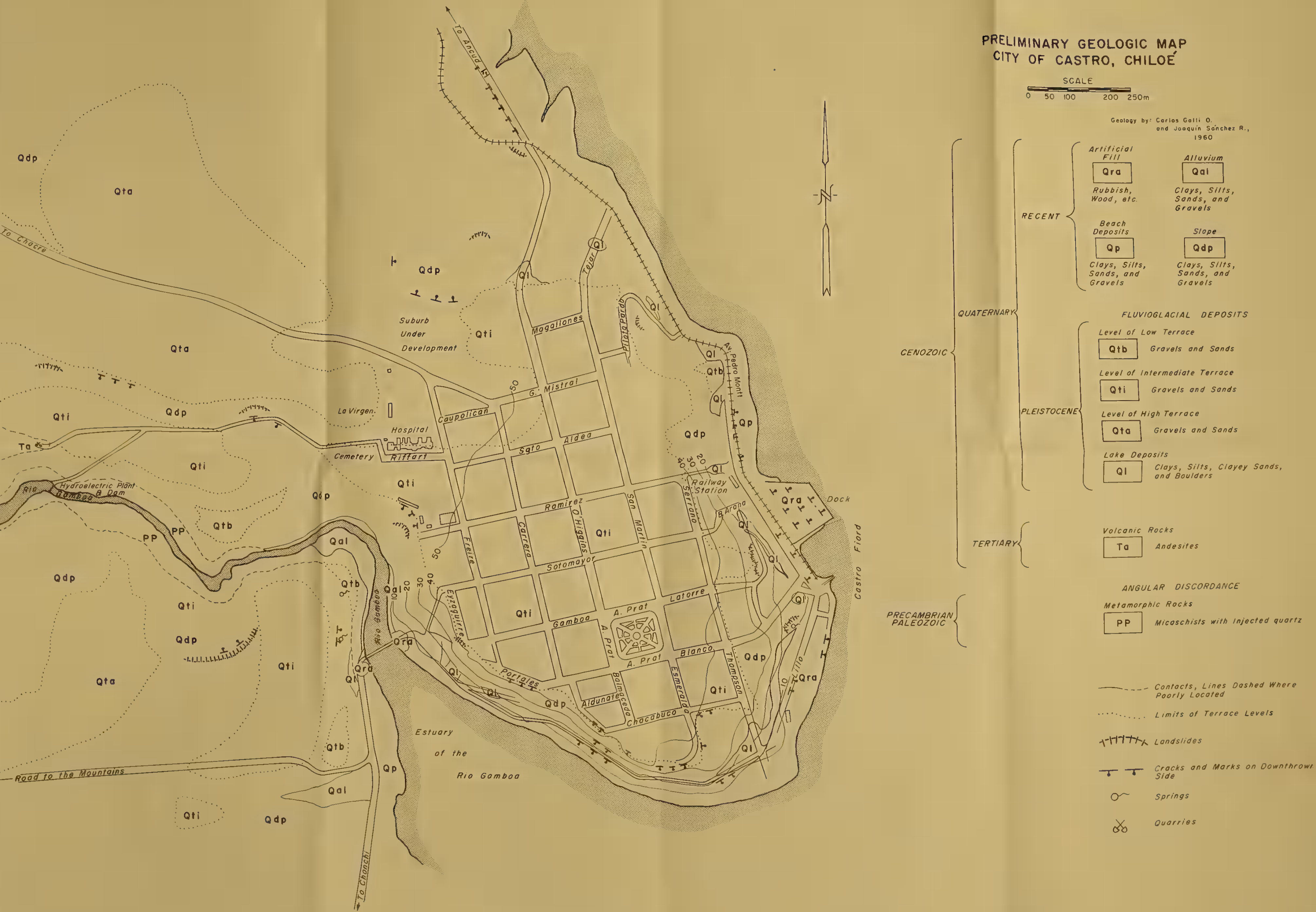

Fig. 2 Geologic Map of Castro and Environs

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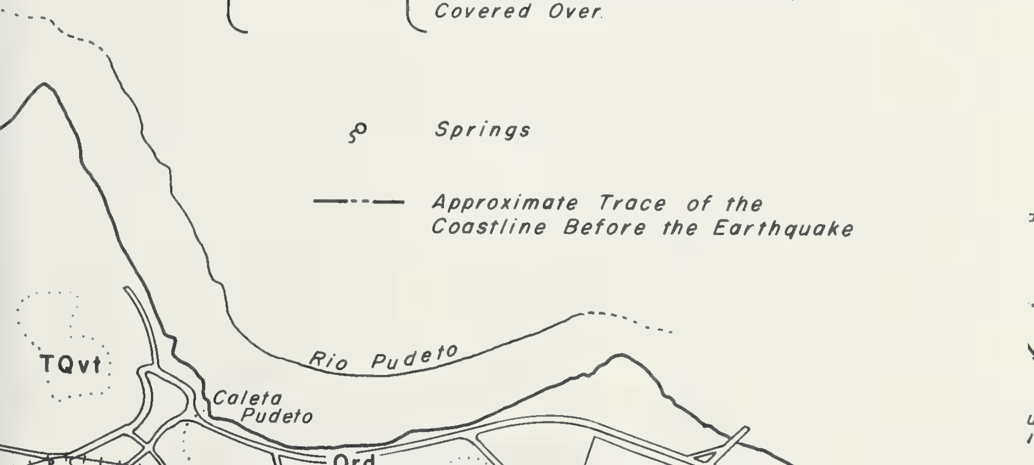
- *Cenozoic*
  - *Quaternary*
    - *Deposits of Artificial Fill* — **Qra** — *Debris, Refuse, Sand, Wood, etc*
    - *Alluvial Deposits* — **Qal** — *Clay, Muddy Sand, and Gravel*
    - *Terrace Deposits* — **Qt** — *Clay, Muddy Sand, and Gravel*
    - *Playa Deposits* — **Qp** — *Clay, Muddy Sand, and Gravel*
  - *Quaternary-Tertiary*
    - *Volcanic Complex of Ancud* — **TQv** **TQvt** — *Andesite, Calcareous Tufa, and Agglomerate Breccia.* **TQvt**, *where Covered Over.*

ᘓ *Springs*

—··— *Approximate Trace of the Coastline Before the Earthquake*



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Relation Between the Geology and the Effects of the Earthquakes of May 1960 in the City of Ancud and Vicinity, Chiloé *Carlos Galli O. and Joaquin Sanchez R.*

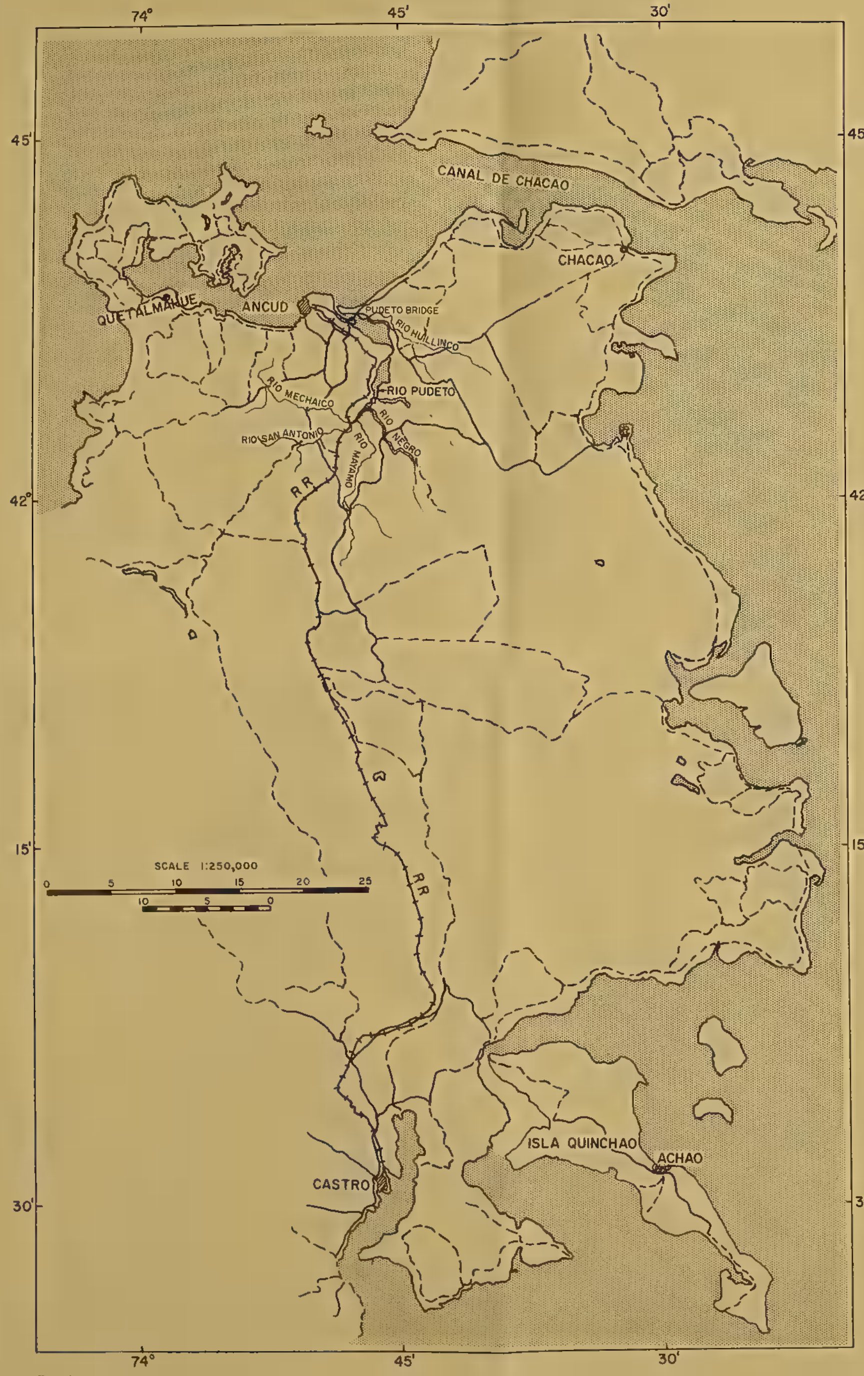

Fig. 1

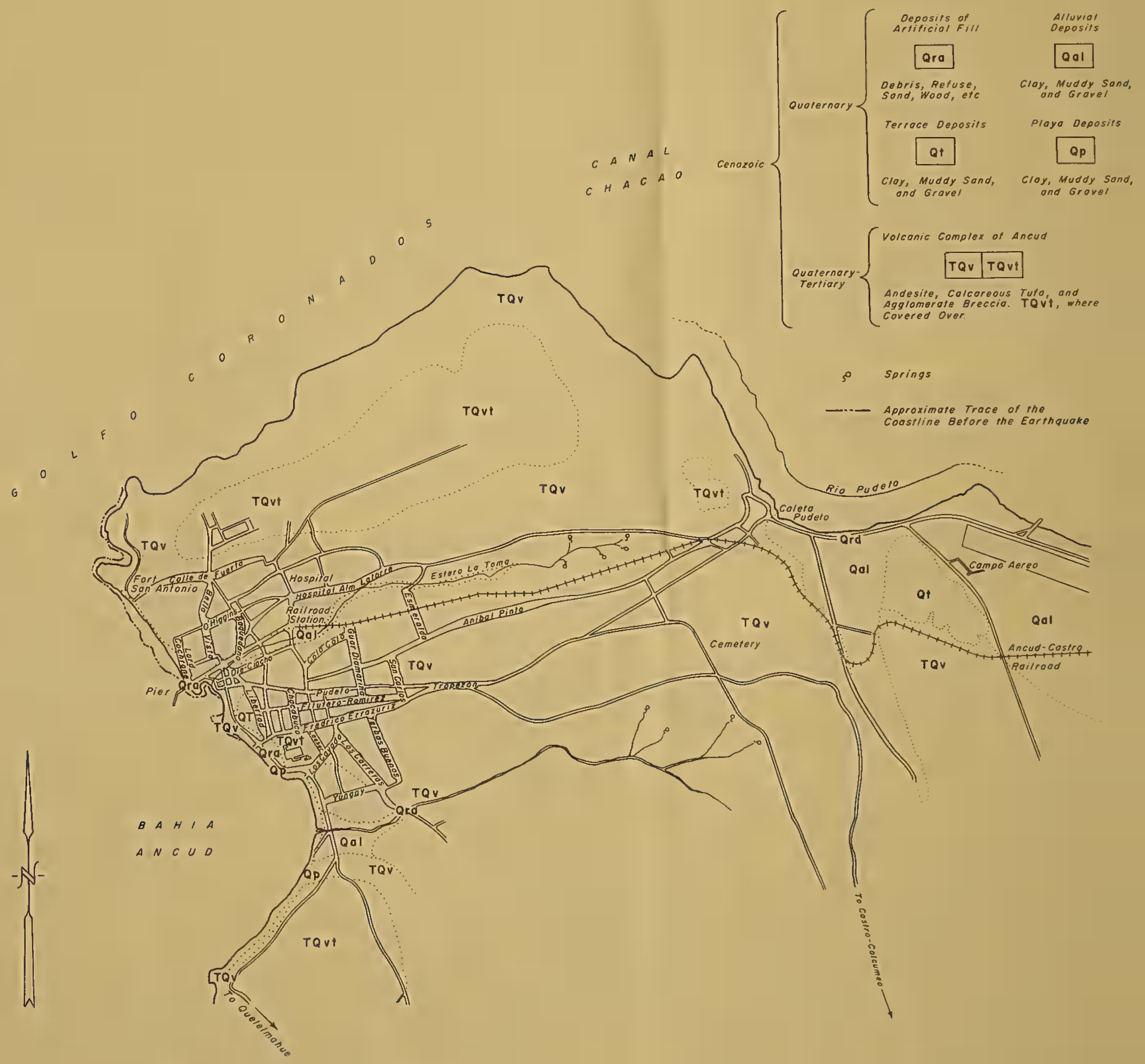

Fig. 2.

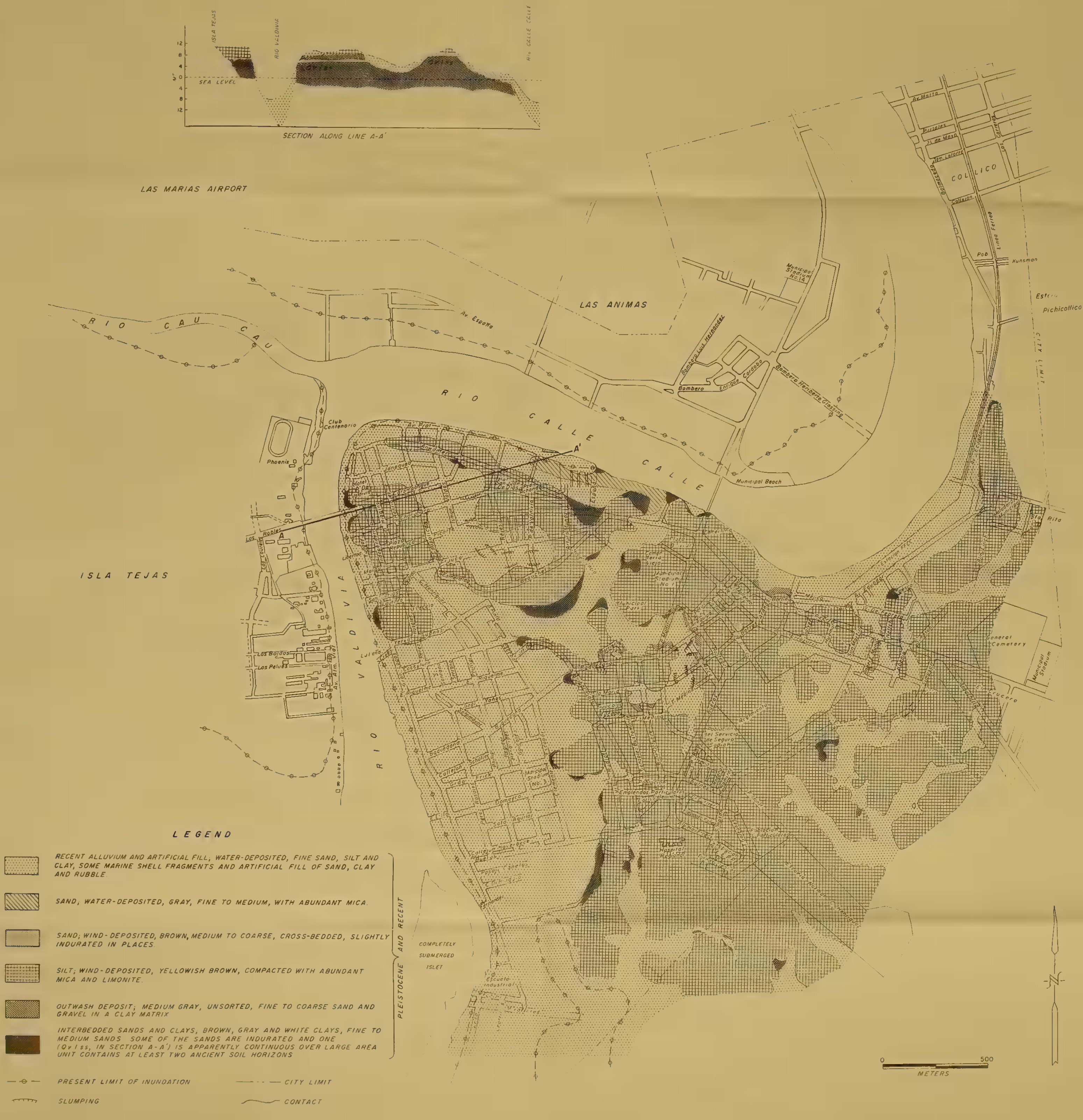
ISLA TEJAS
RIO VALDIVIA
RIO CALLE CALLE
SEA LEVEL
12
8
4
0
4
8
12
SECTION ALONG LINE A-A'
LAS MARIAS AIRPORT
LAS ANIMAS
ISLA TEJAS
RIO CAU CAU
RIO CALLE CALLE
RIO VALDIVIA
COLLICO
Municipal Stadium No. 4
Municipal Beach
Club Centenario
Phoenix
Los Bajdos
Los Pelues
General Cemetery
Municipal Stadium
Municipal Stadium No. 3
Municipal Stadium No. 1
Hospital Regional
Escuela Industrial
COMPLETELY SUBMERGED ISLET
CITY LIMIT
Sta. Rita
Pichicollico
A
A'
0
500
METERS
LEGEND
RECENT ALLUVIUM AND ARTIFICIAL FILL, WATER-DEPOSITED, FINE SAND, SILT AND CLAY, SOME MARINE SHELL FRAGMENTS AND ARTIFICIAL FILL OF SAND, CLAY AND RUBBLE
SAND, WATER-DEPOSITED, GRAY, FINE TO MEDIUM, WITH ABUNDANT MICA
SAND; WIND-DEPOSITED, BROWN, MEDIUM TO COARSE, CROSS-BEDDED, SLIGHTLY INDURATED IN PLACES
SILT; WIND-DEPOSITED, YELLOWISH BROWN, COMPACTED WITH ABUNDANT MICA AND LIMONITE
OUTWASH DEPOSIT; MEDIUM GRAY, UNSORTED, FINE TO COARSE SAND AND GRAVEL IN A CLAY MATRIX
INTERBEDDED SANDS AND CLAYS, BROWN, GRAY AND WHITE CLAYS, FINE TO MEDIUM SANDS. SOME OF THE SANDS ARE INDURATED AND ONE (Qv I ss, IN SECTION A-A') IS APPARENTLY CONTINUOUS OVER LARGE AREA UNIT CONTAINS AT LEAST TWO ANCIENT SOIL HORIZONS
PLEISTOCENE AND RECENT
PRESENT LIMIT OF INUNDATION
CITY LIMIT
SLUMPING
CONTACT

Fig. 1. Map of Valdivia Indicating Topographic and Geologic Structure.

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Geologic Report on the Effects of the Earthquake of 22 May 1960 in the City of Puerto Varas   *Herbert Thomas, William Bowes, and Nelson Bravo S.*

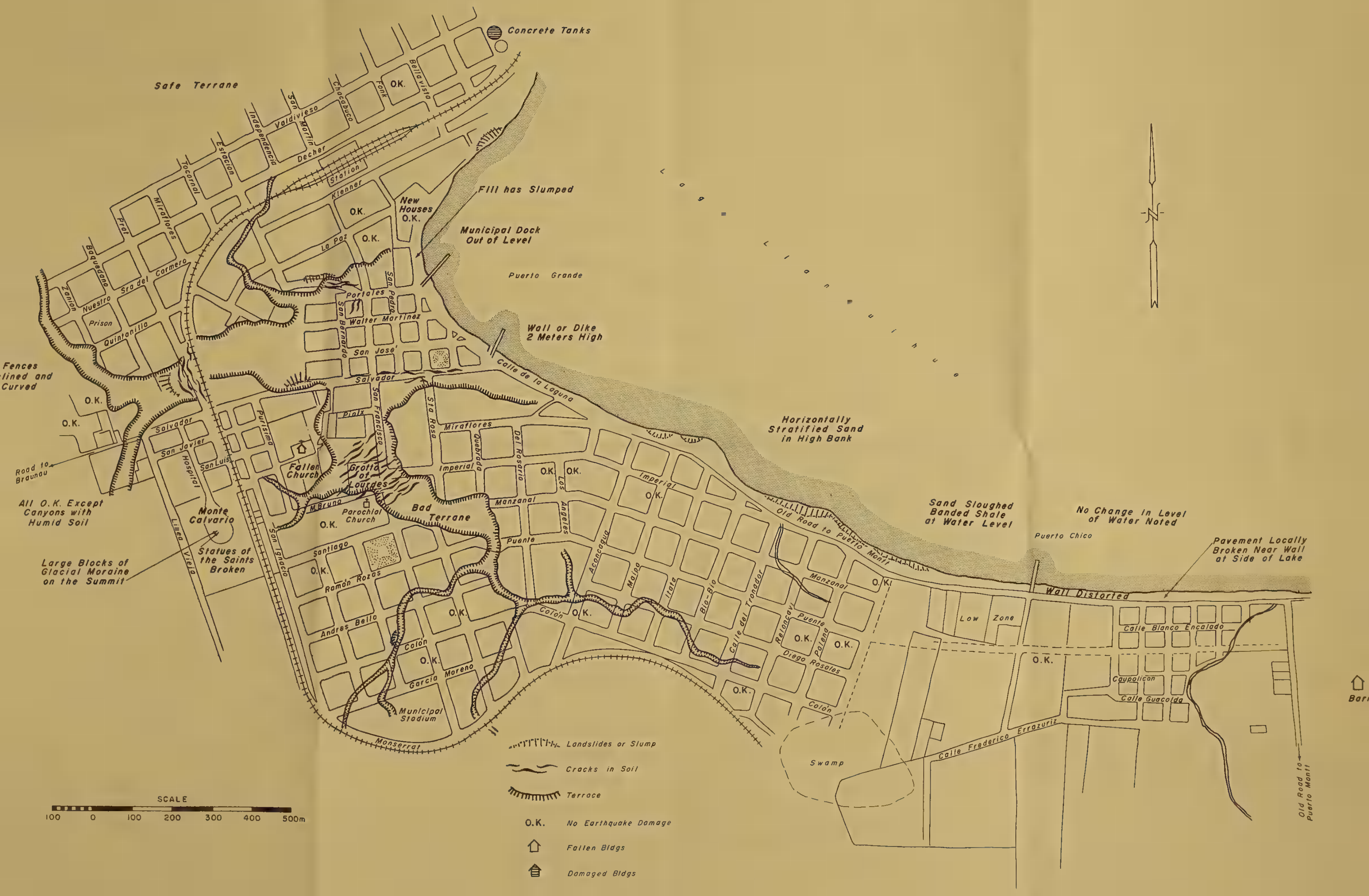


Fig. 2. City Map of Puerto Varas.

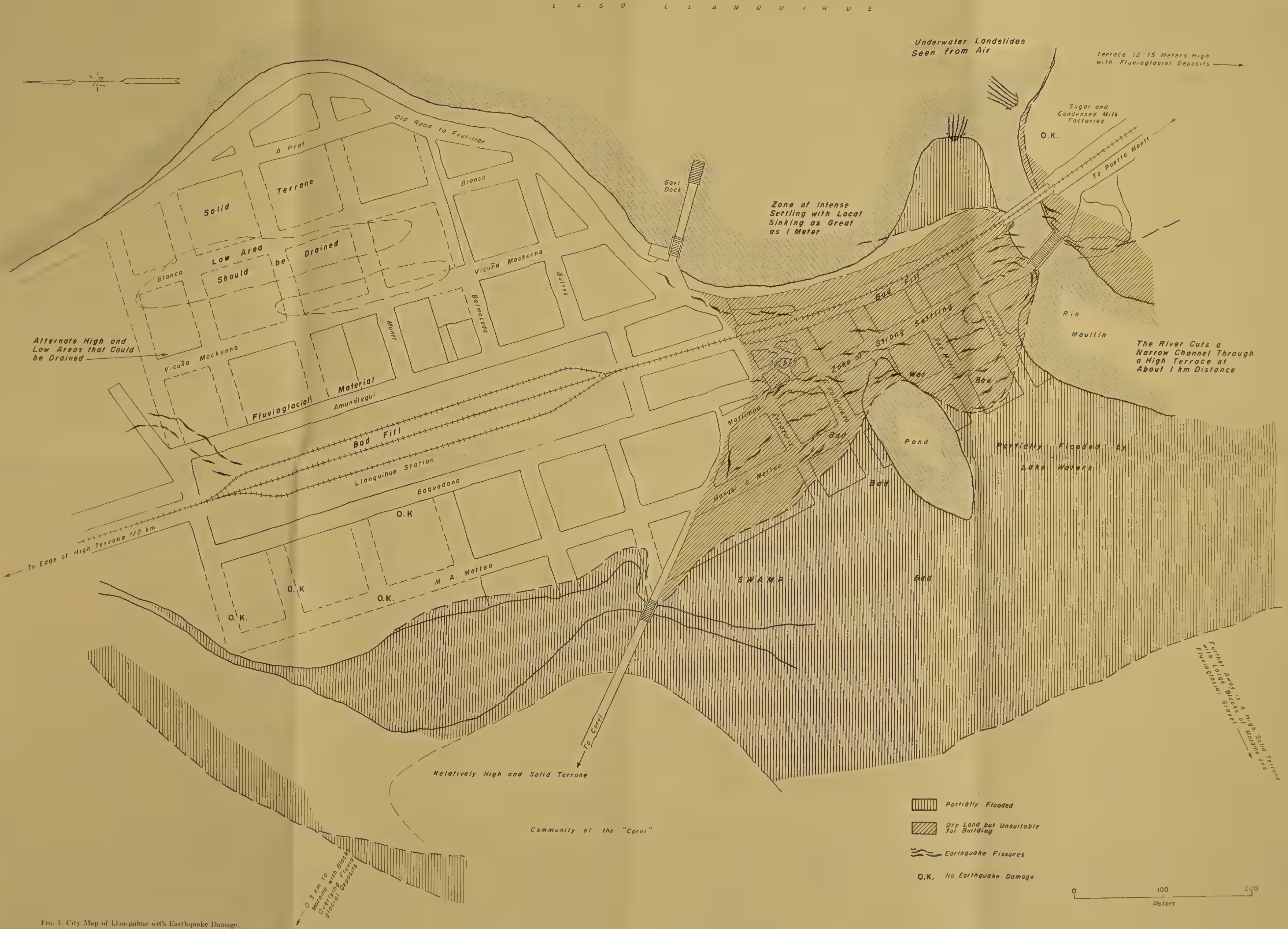

LAGO LLANQUIHUE
Underwater Landslides Seen from Air
Terrace 12-15 Meters High with Fluvioglacial Deposits
Sugar and Condensed Milk Factories
O.K.
To Puerto Montt
Govt Dock
Zone of Intense Settling with Local Sinking as Great as 1 Meter
Rio Maullin
The River Cuts a Narrow Channel Through a High Terrace at About 1 km Distance
Old Road to Frutillar
A Prat
Blanco
Solid Terrone
Low Area Should be Drained
Vicuña Mackenna
Bulnes
Balmaceda
Montt
Alternate High and Low Areas that Could be Drained
Fluvioglacial Material
Amunátegui
Bad Fill
Llanquihue Station
Baquedano
O.K
M. A. Mattea
O.K.
To Edge of High Terrone 1/2 km
Zone of Strong Settling
Plaza
Matlimpa
Errazuriz
Valdivieso
San Martin
Candelaria
Wet
Bad
Pond
Partially Flooded by Lake Waters
Manuel A. Matteo
SWAMP
To Corvi
Relatively High and Solid Terrone
Community of the "Corvi"
0.3 km to Moraine with Blocks Overlying Fluvioglacial Deposits
Further Away is a High Solid Terrone with Large Blocks of Moraine and Fluvioglacial Gravel
Partially Flooded
Dry Land but Unsuitable for Building
Earthquake Fissures
O.K. No Earthquake Damage
0
100
200
Meters

Fig. 1. City Map of Llanquihue with Earthquake Damage.

SHEET 10
551.22
S133
sheet 10

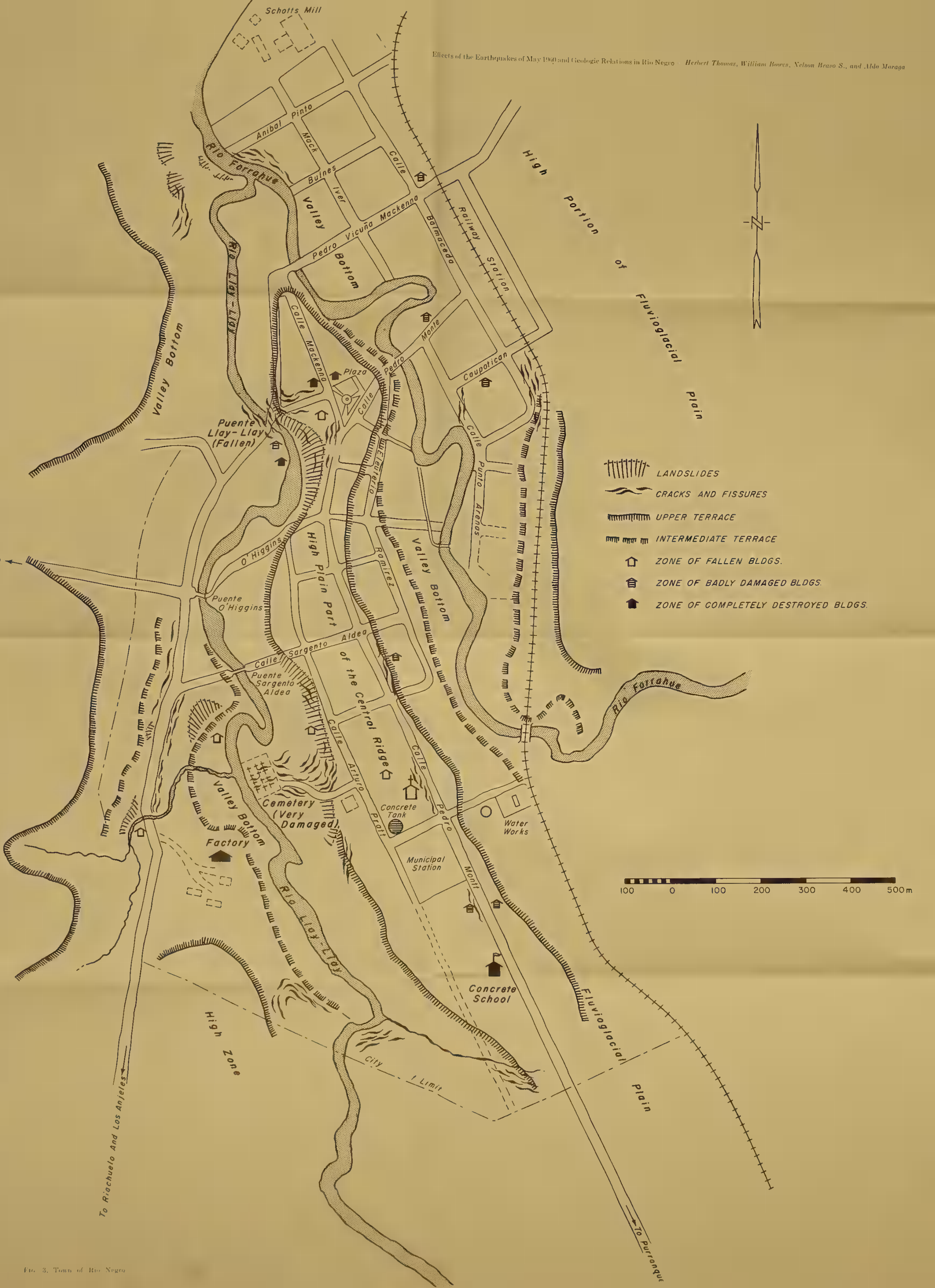
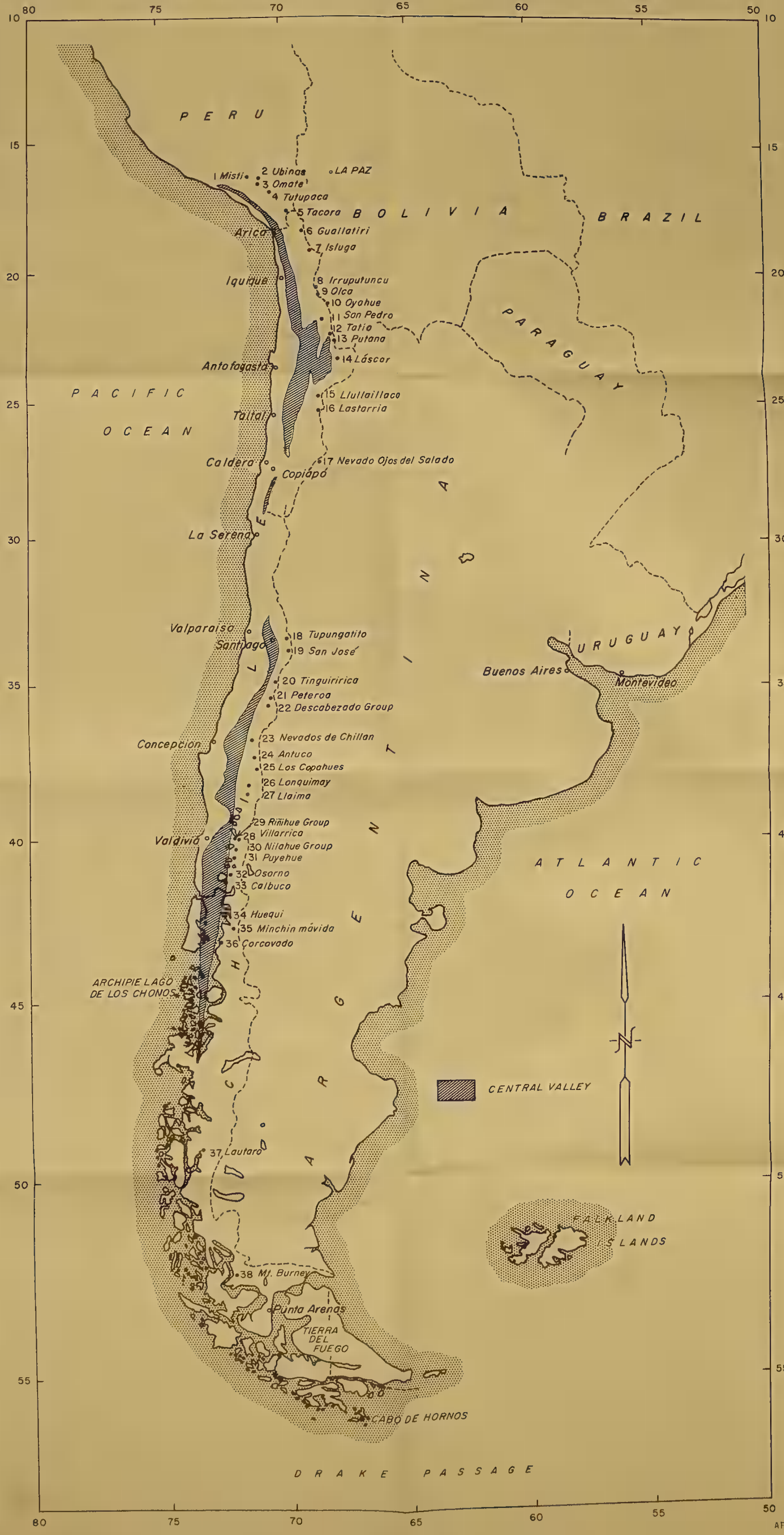


Fig. 3. Town of Rio Negro


80
75
70
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60
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55
PERU
BOLIVIA
BRAZIL
PARAGUAY
URUGUAY
PACIFIC OCEAN
ATLANTIC OCEAN
CHILE
ARGENTINA
LA PAZ
1 Misti
2 Ubinas
3 Omate
4 Tutupaca
5 Tacora
6 Guallatiri
7 Isluga
8 Irruputuncu
9 Olca
10 Oyahue
11 San Pedro
12 Tatio
13 Putana
14 Láscar
15 Llullaillaco
16 Lastarria
17 Nevado Ojos del Salado
18 Tupungatito
19 San José
20 Tinguiririca
21 Peteroa
22 Descabezado Group
23 Nevados de Chillan
24 Antuco
25 Los Copahues
26 Lonquimay
27 Llaima
29 Riñihue Group
28 Villarrica
30 Nilahue Group
31 Puyehue
32 Osorno
33 Calbuco
34 Huequi
35 Minchin mávida
36 Corcovado
37 Lautaro
38 Mt. Burney
Arica
Iquique
Antofagasta
Taltal
Caldera
Copiapó
La Serena
Valparaíso
Santiago
Concepción
Valdivia
Buenos Aires
Montevideo
ARCHIPIELAGO DE LOS CHONOS
Punta Arenas
TIERRA DEL FUEGO
CABO DE HORNOS
FALKLAND ISLANDS
DRAKE PASSAGE
CENTRAL VALLEY
N

APPENDIX A

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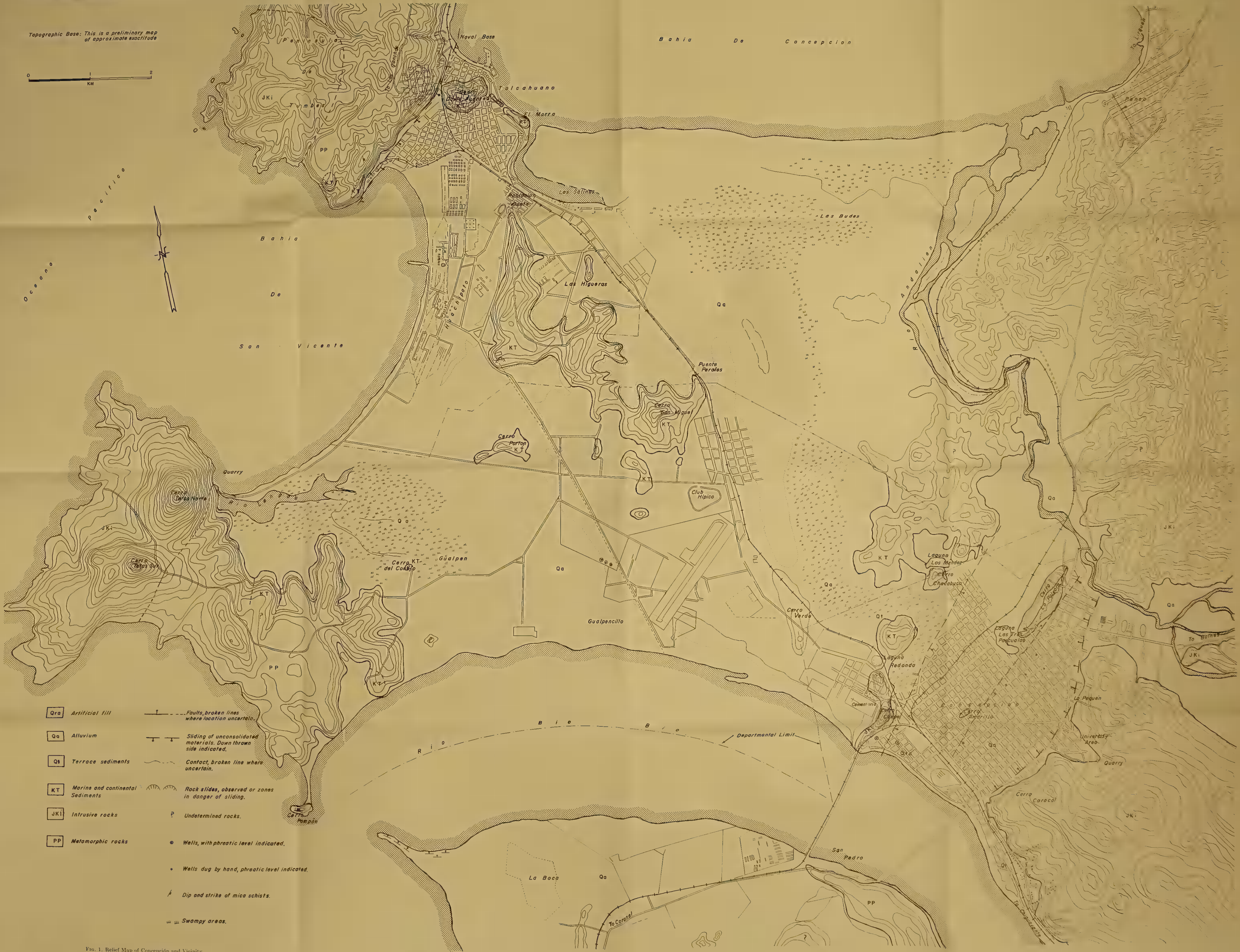


Fig. 1. Relief Map of Concepción and Vicinity.

Relation Between Geology and the Damage in Puerto Montt, Chile, Caused by the Earthquake of 22 May 1960 *Ernest Dobrovolny, Richard Lemke, William Bowes, Herbert Thomas, and Nelson Bravo S.*

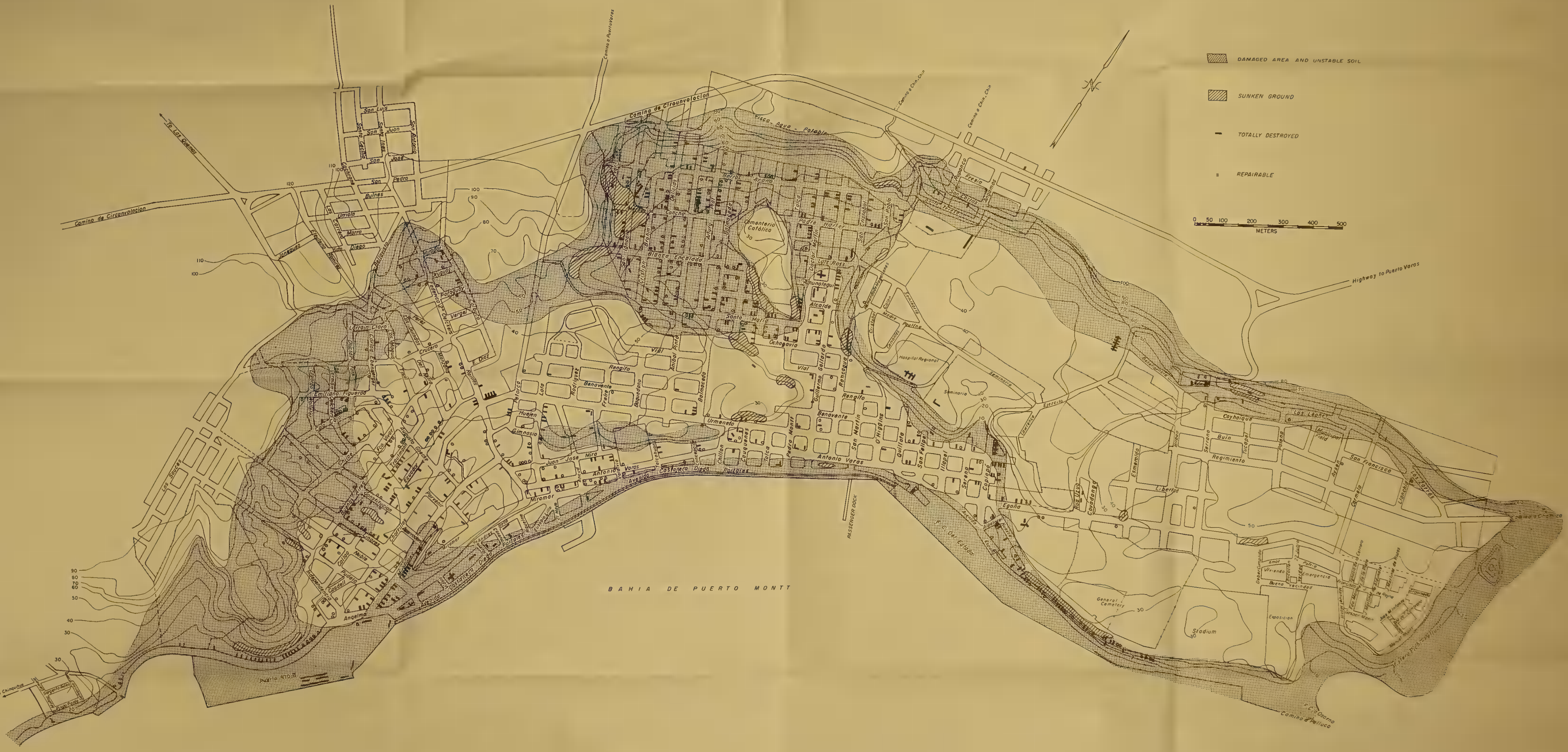
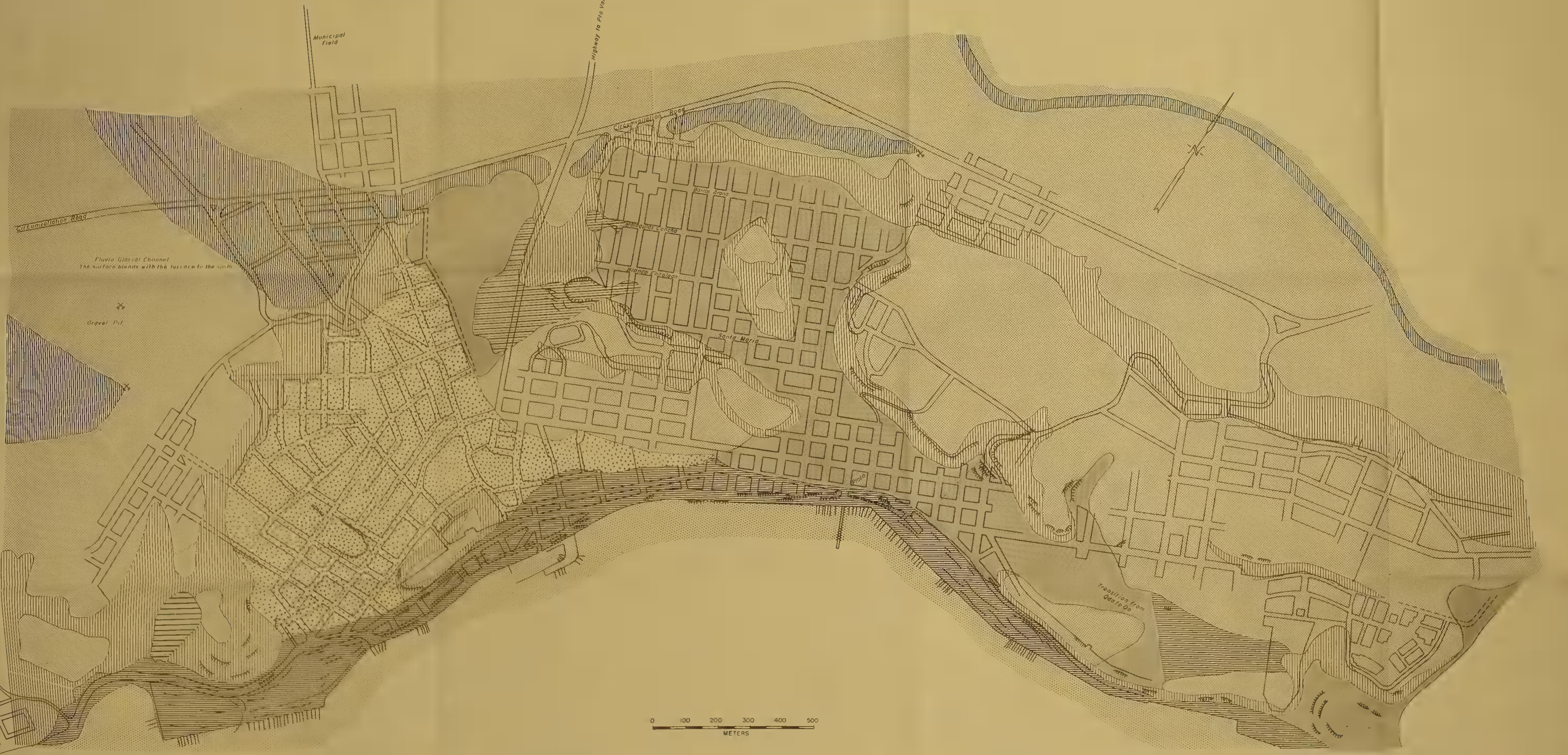


FIG. 1. Map of Puerto Montt.

Relation Between Geology and the Damage in Puerto Montt, Chile, Caused by the Earthquake of 22 May 1960 *Ernest Dobrovolny, Richard Lemke, William Bowes, Herbert Thomas, and Nelson Bravo S.*

SHEET 12

557.83 ... Sheet 12



▤ ARTIFICIAL FILL

GRAVEL, SAND, BRICK, WOOD, AND MUD, UNCONSOLIDATED, SEVERAL METERS THICK ALONG THE COAST.

▒ BEACH DEPOSITS

PRINCIPALLY SAND ALONG THE BAY FRONT, THICKNESS UNKNOWN.

▤ DEPOSITS OF MUD FLOWS, DEBRIS FLOWS, AND LANDSLIDES FROM EARTHQUAKE OF 22 MAY 1960.

SILT, SAND, GRAVEL, AND MUD, POORLY CONSOLIDATED, SEVERAL METERS THICK IN PLACES.

▤ DEBRIS FLOW OF 1957

SILT, GRAVEL, SAND, AND HUMIC MATERIAL

▨ DEPOSITS OF MUD FLOWS, DEBRIS FLOWS, LANDSLIDES, AND OLD ALLUVIUM.

SILT, SAND, GRAVEL, AND MUD, UNCONSOLIDATED, MOVED DOWNHILL IN HISTORIC AND PREHISTORIC TIMES. INCLUDES SAND AND ALLUVIAL GRAVEL, ESPECIALLY IN THE COMMERCIAL SECTORS, AND ALSO SOME ARTIFICIAL FILL.

▥ COLLUVIAL DEPOSITS AND LANDSLIPS ON STRONG SLOPES.

MOSTLY SILTY WEATHERED CLAY; SOME SAND AND GRAVEL, GENERALLY FROM 1 TO 2 METERS THICK, POORLY DEFINED BEDS SLOPING DOWNHILL. IN PARTS INCLUDES ALLUVIAL FANS.

▥ TERMINAL MORAINE

MORAINIC MATERIAL COMPOSED OF SAND, GRAVEL, COBBLES, AND BOULDERS, UP TO 1 METER DIAMETER, UNSTRATIFIED, INTERCALATIONS OF STRATIFIED SAND AND GRAVEL.

▒ GLACIOFLUVIAL SEDIMENTS OF TERRACE CUTS

MOSTLY CLEAN SAND OF GRAY COLOR, STRATIFIED, SOME GRAVEL, FORMS CUT TERRAIN.

░ GLACIOFLUVIAL SEDIMENTS OF THE WIDE TERRACES

MAINLY WELL-STRATIFIED BEDS OF SAND AND GRAVEL FORMS ALMOST FLAT WIDE TERRACES AT DIFFERENT LEVELS. INCLUDES SAND AND GRAVEL IN GLACIOFLUVIAL CHANNELS.

▦ LACUSTRIAN DEPOSITS

SILT AND CLAY FINELY STRATIFIED IN THE SOUTHWEST PART OF THE CITY (VARVED?). MORE THAN 19 METERS THICK

⌒ CONTACT: THE MAJORITY OF CONTACTS ARE ONLY APPROXIMATELY LOCATED.

⌒ ⌒ FRACTURES: IN LOCATIONS WHERE THERE ARE OBSERVATIONS, THE TEETH INDICATE THE SIDE THAT WENT DOWN.

┬ RETENTION WALL ON THE COAST; THE LONG MARKS INDICATE THE DIRECTION OF MOVEMENT OF THE WALLS.

⚒ GRAVEL PIT.

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